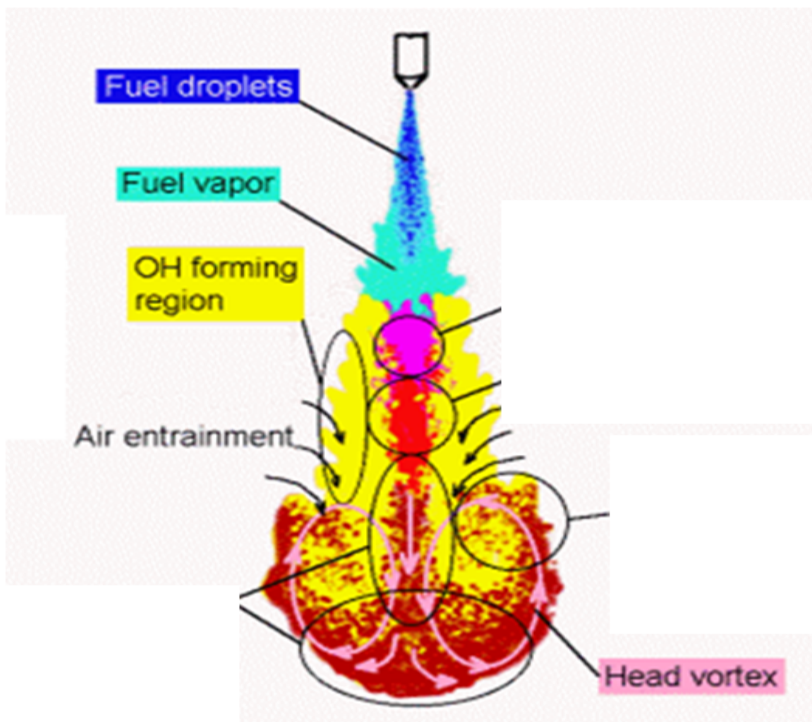
16MEE03 & Advanced I.C Engines

Care for Occurrence of Heat Addition

- Occurrence of Heat Addition in SI Engine : A Child Care Event.
- Occurrence of Heat Addition in CI Engine: A Teen Care Event.



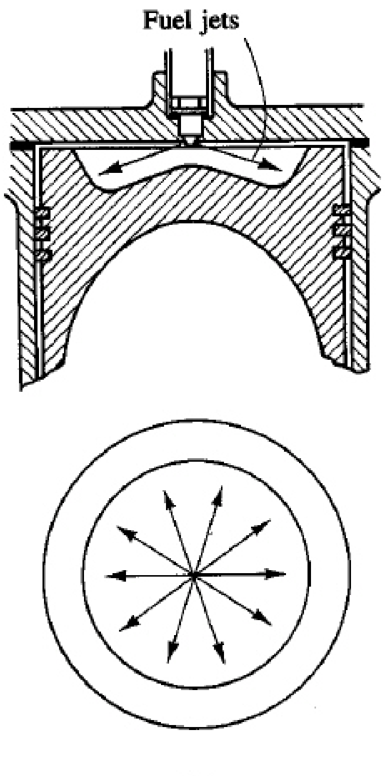
Type of Fuel Vs Combustion Strategy

- Highly volatile with High self Ignition Temperature: Spark Ignition. Ignition after thorough mixing of air and fuel.
- Less Volatile with low self Ignition Temperature: Compression Ignition , Almost simultaneous mixing & Ignition.

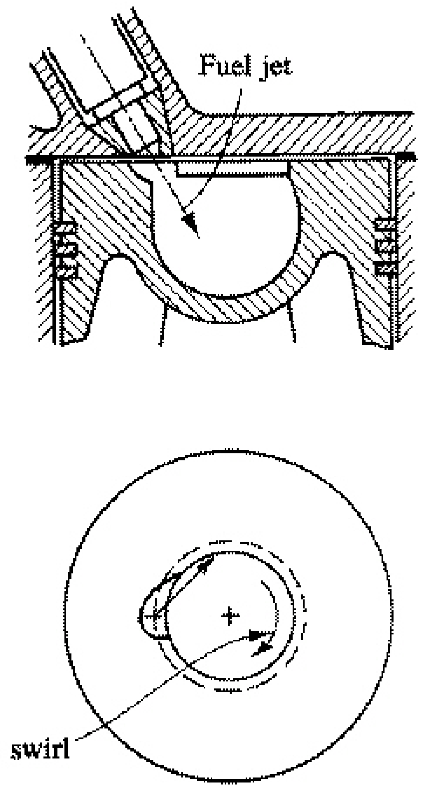
Compression Ignition Engines

- Two basic categories of CI engines:
- **Indirect-injection Engine** – 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.
- **Direct-injection Engine** – have a single open combustion chamber into which fuel is injected directly

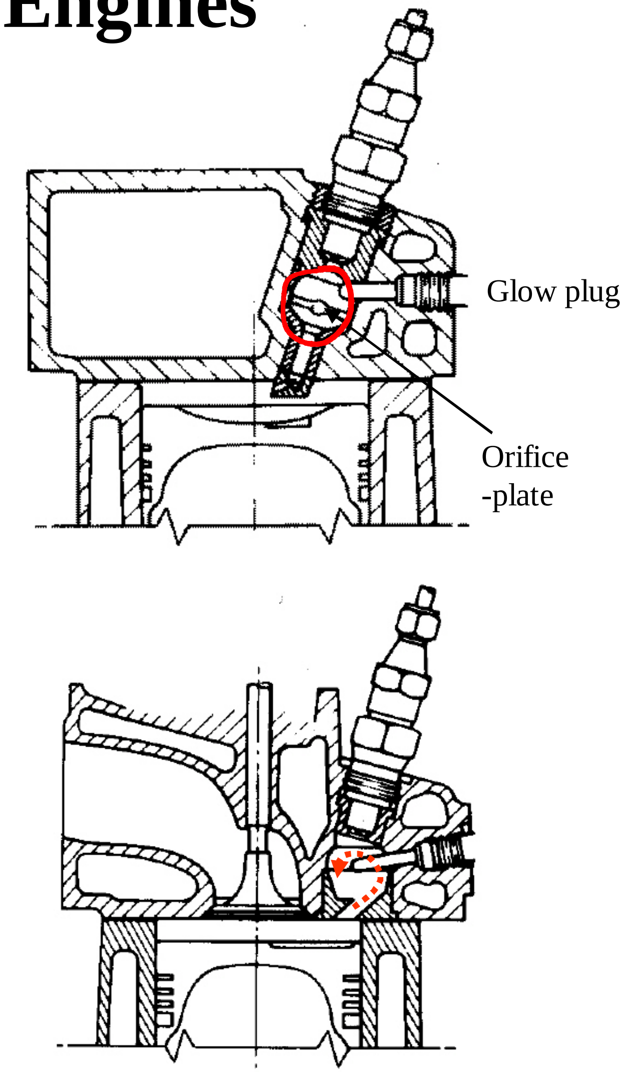
Types of Cylinders for CI Engines



Direct injection:
quiescent chamber

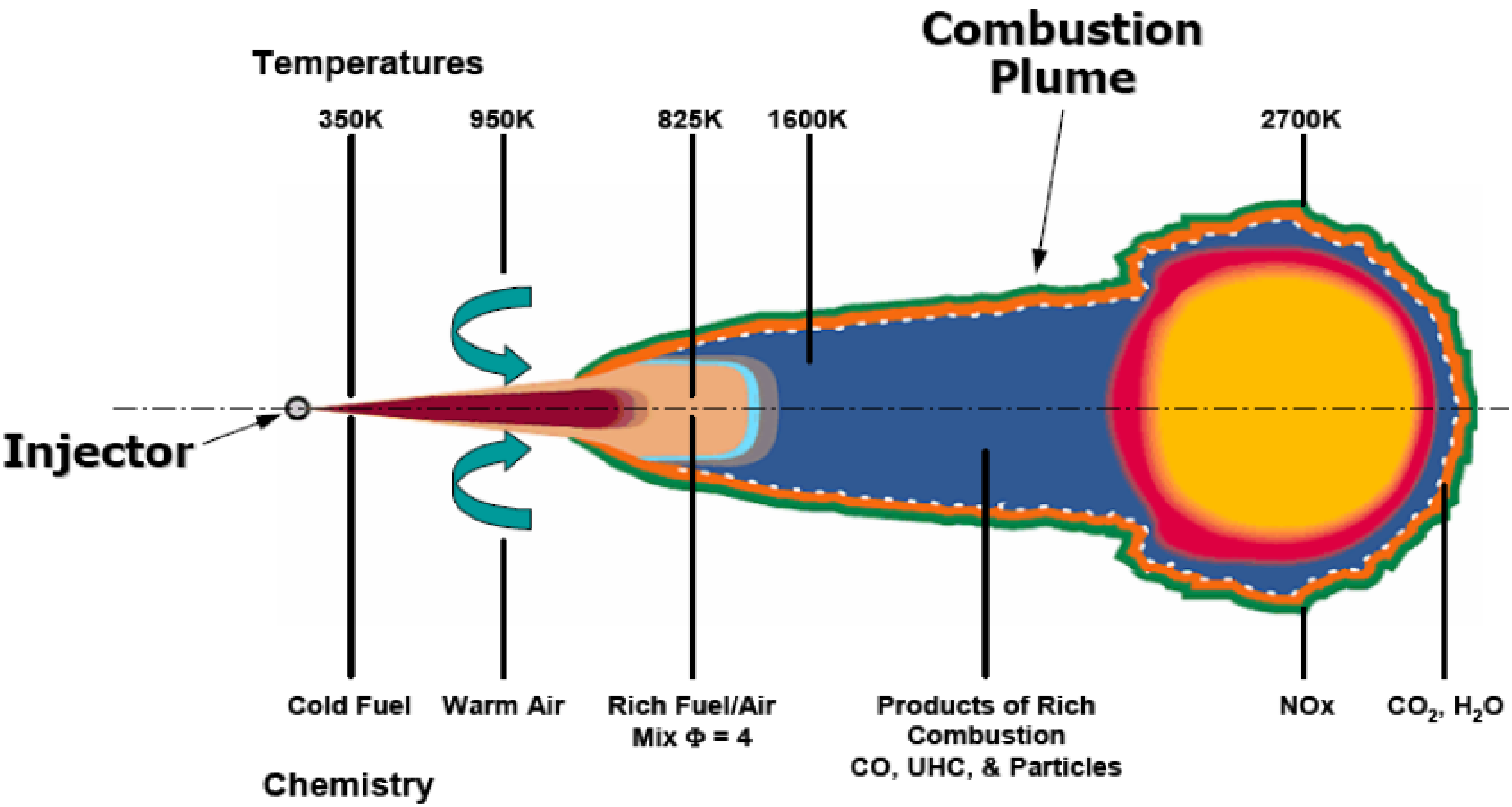


Direct injection:
swirl in chamber

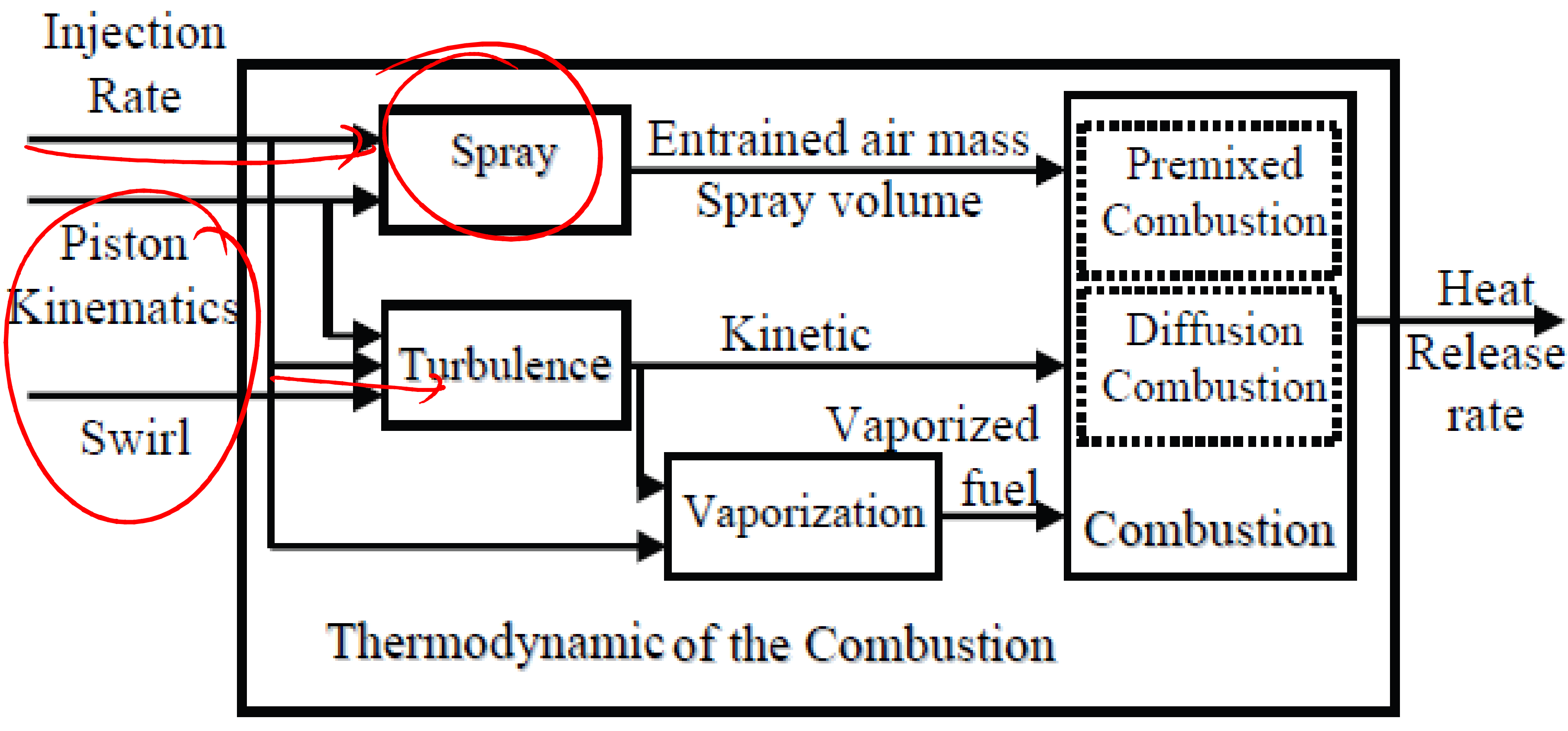


Indirect injection: turbulent and swirl pre-chamber

Schematic of a diesel spray & flame with temperatures and chemistry

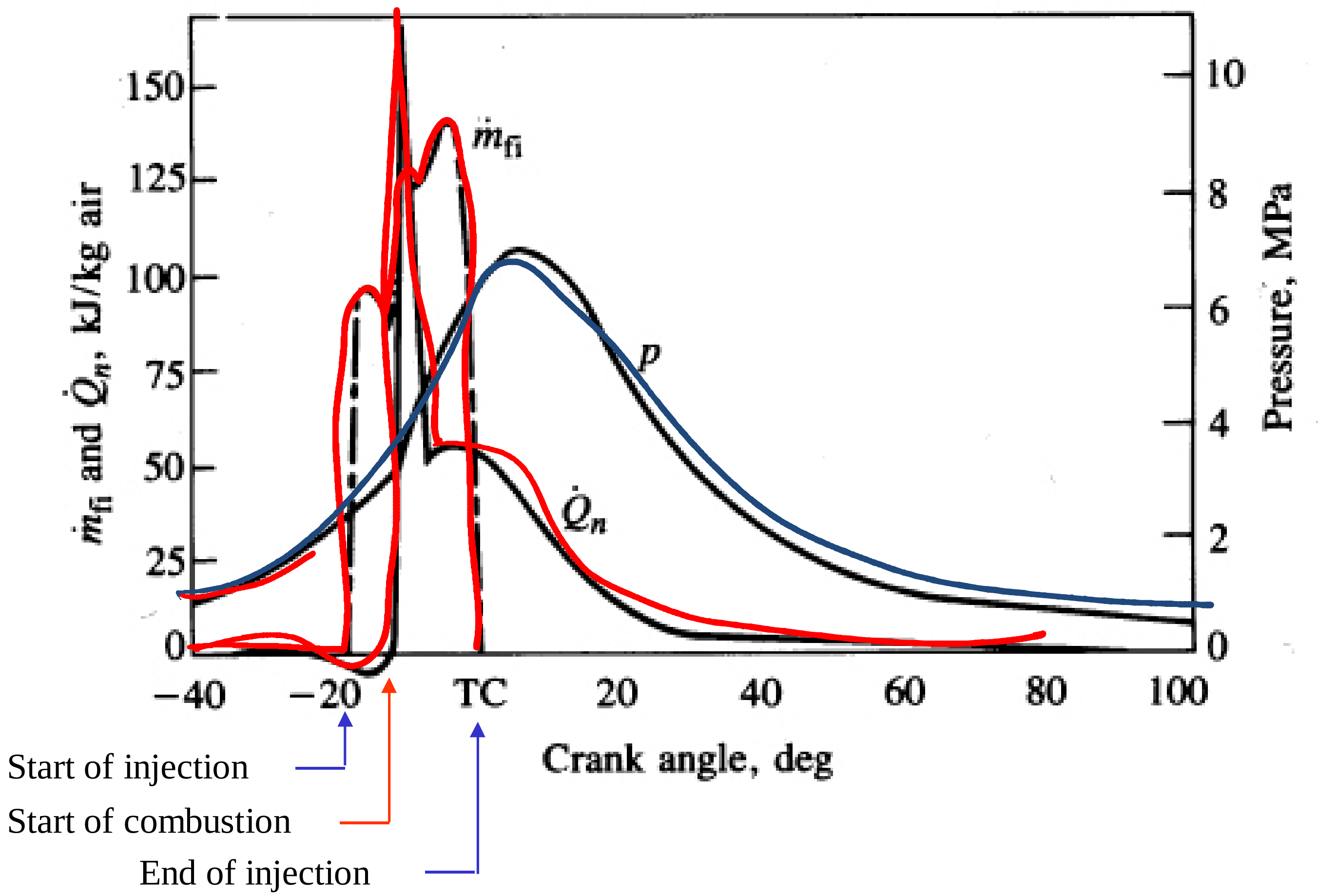


Modeling of Events in CI (Teen) Combustion

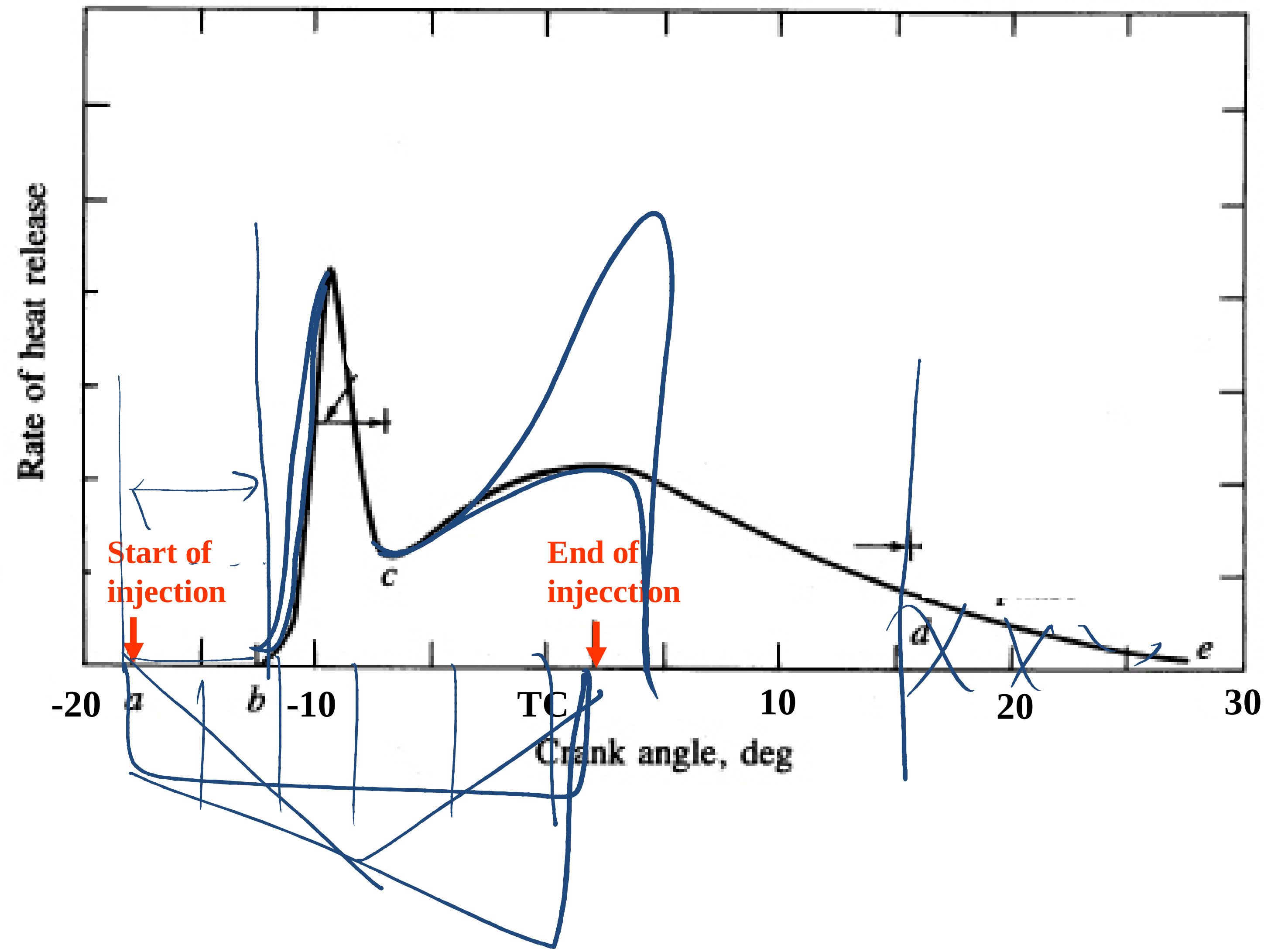


In-Cylinder Processes

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



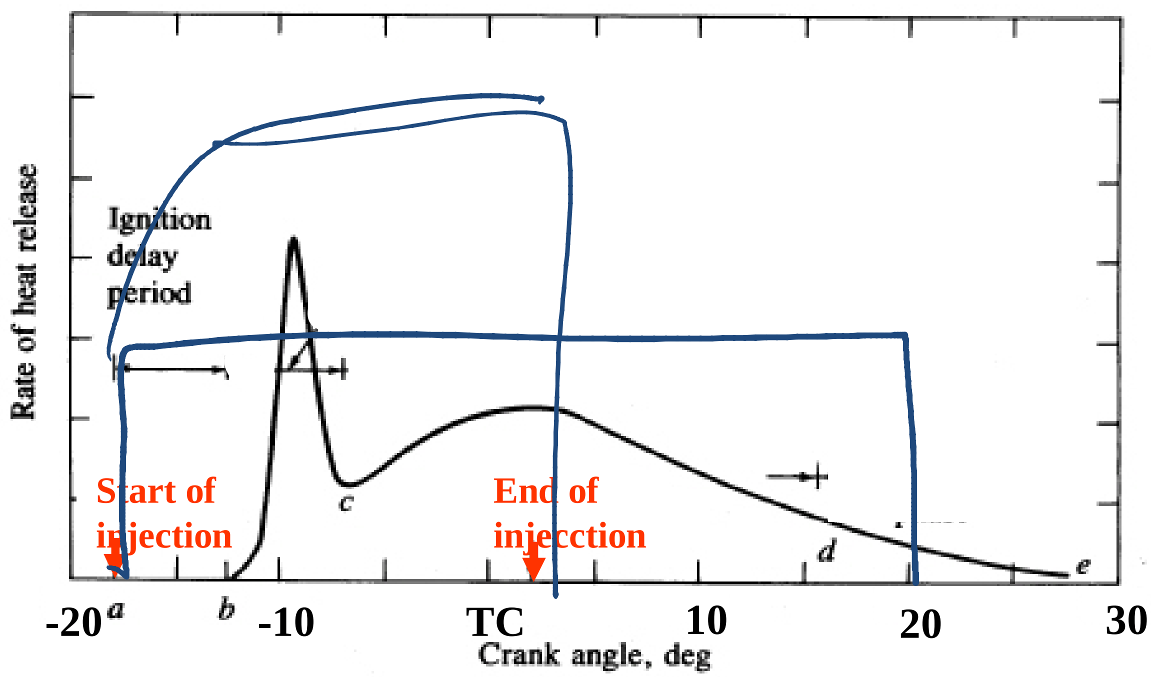
Combustion in CI Engine

The combustion process proceeds by the following stages:

Ignition delay (ab) - fuel is injected directly into the cylinder towards the end of the compression stroke.

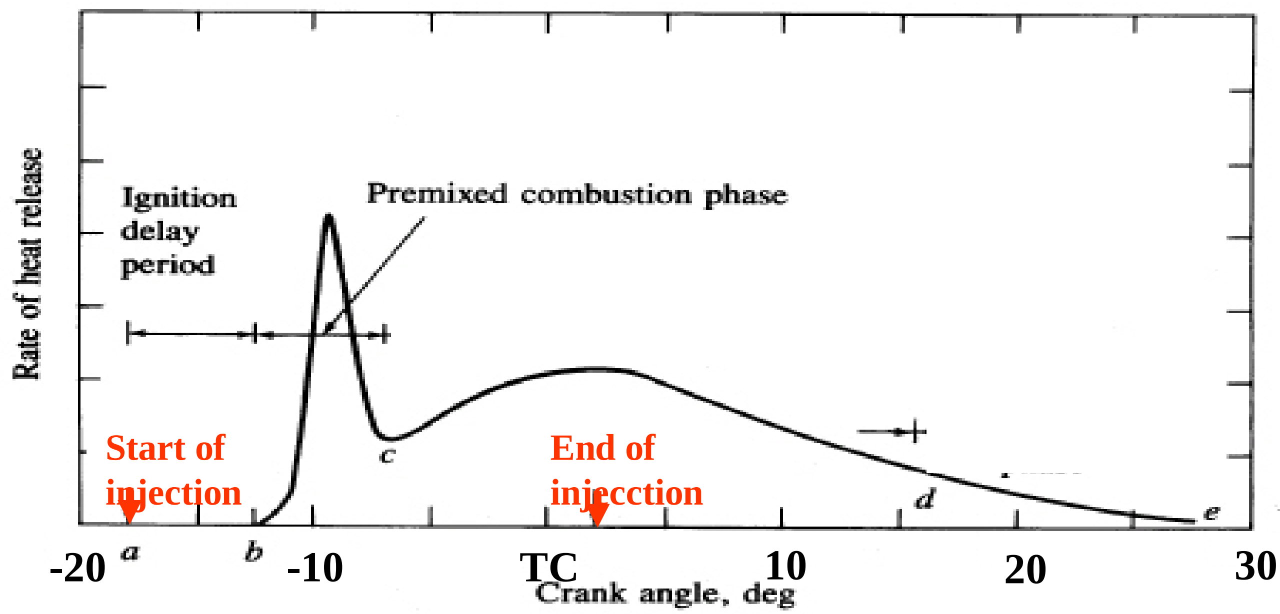
The liquid fuel atomizes into small drops and penetrates into the combustion chamber.

The fuel vaporizes and mixes with the high-temperature high-pressure air.

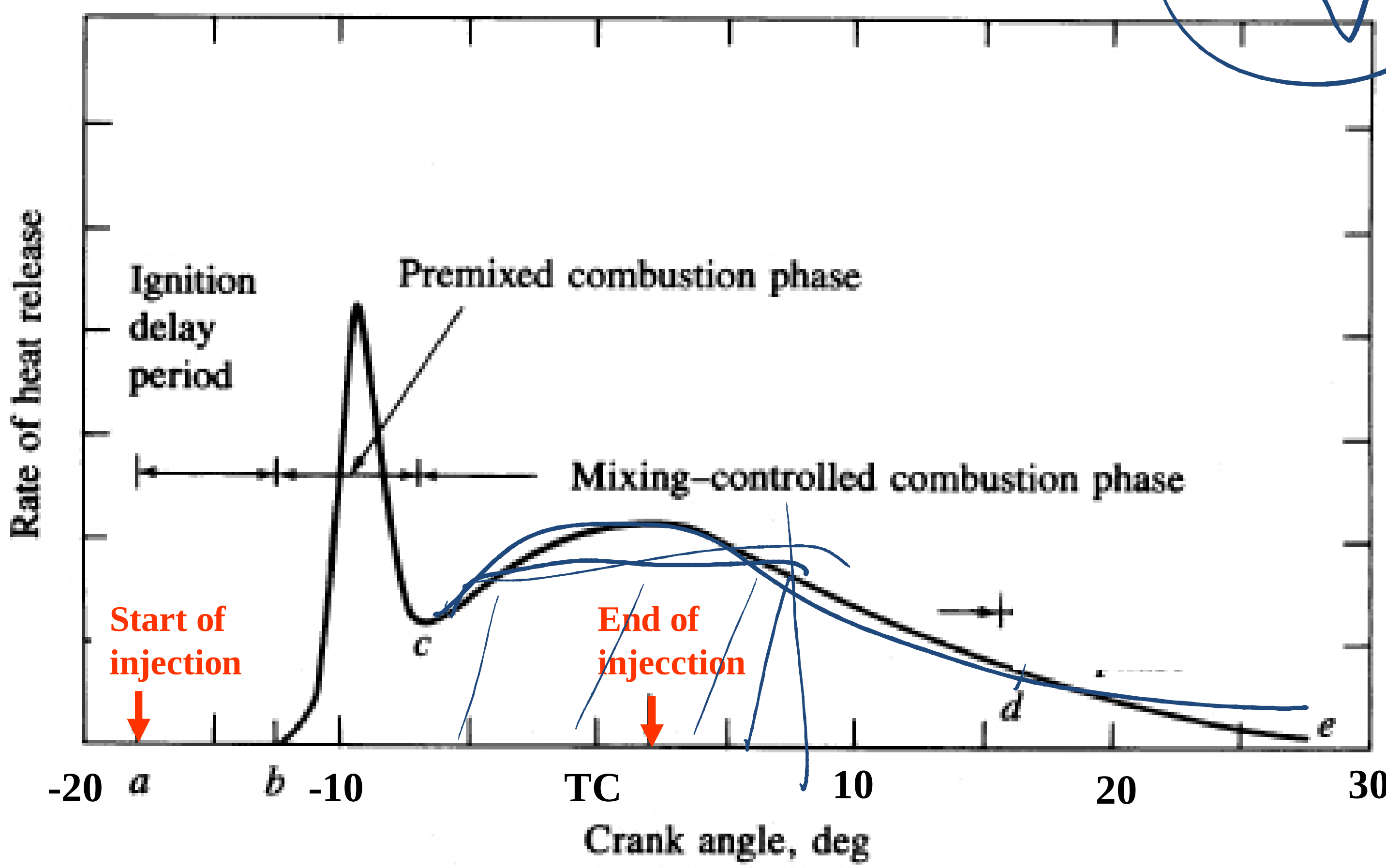


Combustion in CI Engine

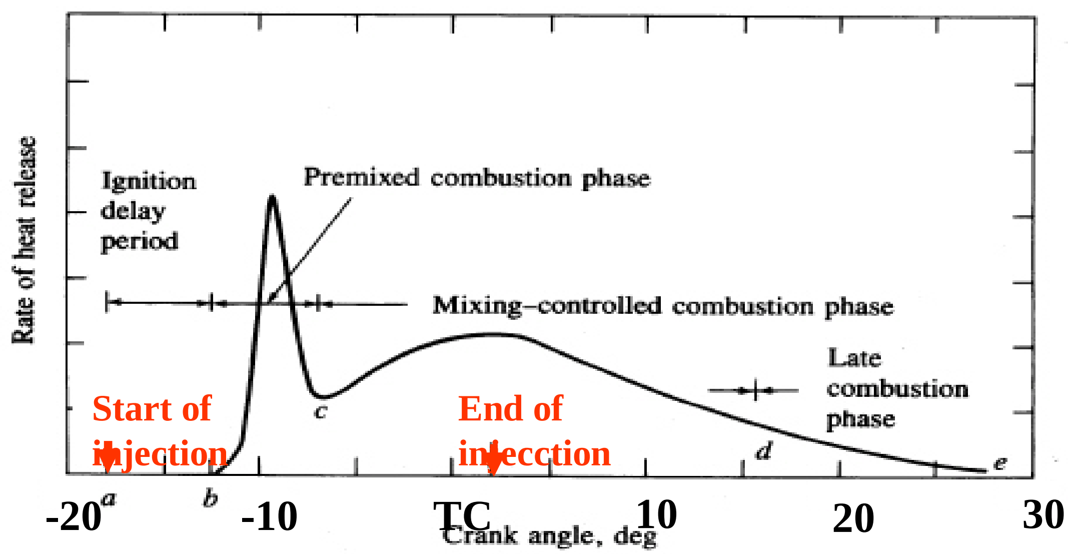
Premixed combustion phase (bc) – combustion of the fuel which has mixed with the air to within the flammability limits (air at high-temperature and high-pressure) during the ignition delay period occurs rapidly in a few crank angles. → Fluid Dynamics



- *Mixing controlled combustion phase (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.



- *Mixing controlled combustion phase (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.
- *Late combustion phase (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.



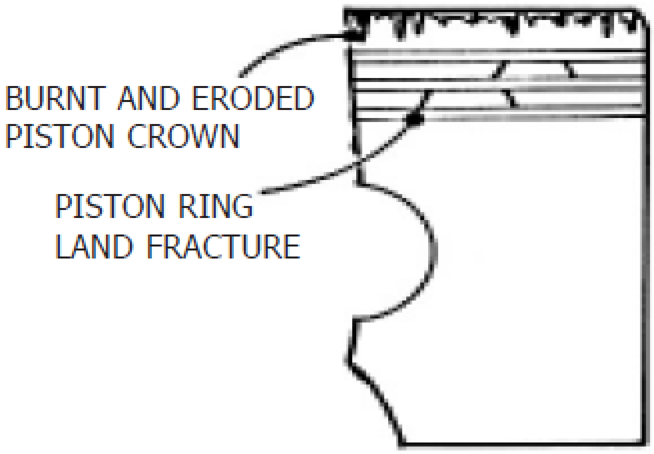
Ignition Delay

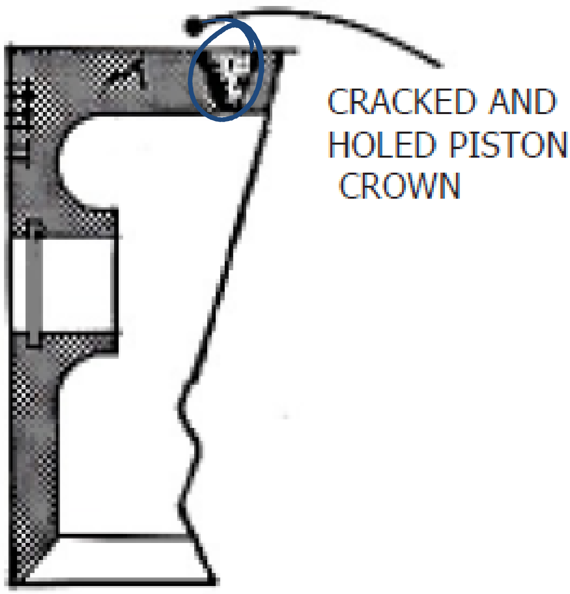
- Ignition delay is defined as the time (or crank angle interval) from when the fuel injection starts to the onset of combustion.
- Both physical and chemical processes must take place before a significant fraction of the fuel chemical energy is released.
- *Physical processes* are fuel spray atomization, 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.
- *Chemical processes:* Autoignition phenomenon in premixed fuel-air.
- Complex **heterogeneous reactions** (reactions occurring on the liquid fuel drop surface) also occur.

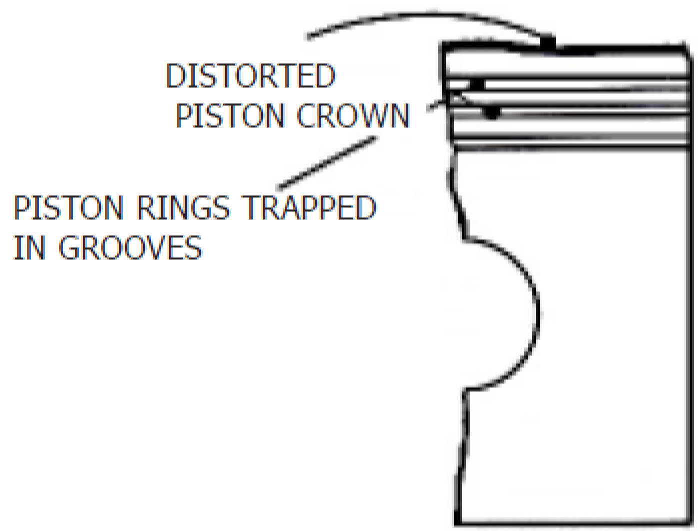
Ignition Delay

- The ignition characteristics of the fuel affect the ignition delay.
- The ignition quality of a fuel is defined by its **cetane number** CN.
- For *low* cetane fuels the ignition delay is long and most of the injected fuel is accumulated in the cylinder before autoignition .
- This leads to rapid combustion.
- Under extreme cases, this produces an audible knocking sound referred to as “diesel knock”.

Combustion Problems in Diesel Engine







Cetane Number

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

•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.

By definition, cetane (n-hexadecane, $C_{16}H_{34}$) has a value of 100.

In the original procedures α-methylnaphtalene ($C_{11}H_{10}$) with a cetane number of zero represented the bottom of the scale.

This has since been replaced by heptamethylnonane, (HMN) has a cetane number of 15, which is a more stable compound.

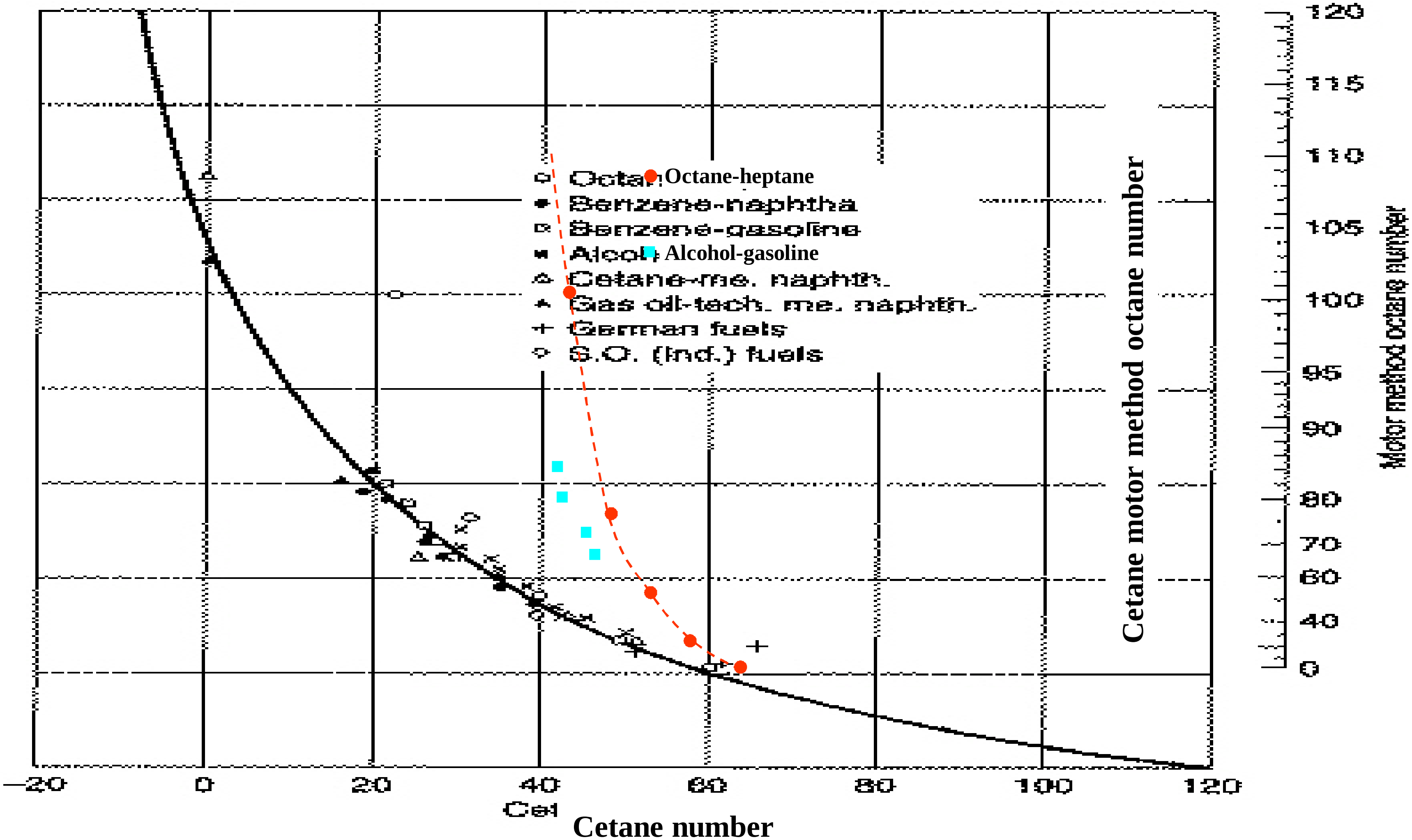
The higher the CN the better the ignition quality, i.e., shorter ignition delay.

The cetane number is given by:

$$CN = (\%\ \mathit{hexadecane}) + 0.15\ (\%\ HMN)$$

Cetane Number versus Octane Number

The octane number and cetane number of a fuel are inversely correlated.



Gasoline is a poor diesel fuel and vice versa.

Hard Ware Design Factors Affecting Ignition Delay Time

•*<u>Injection timing</u>* – At normal engine conditions the minimum delay occurs with the start of injection at about 10-15 BTC.

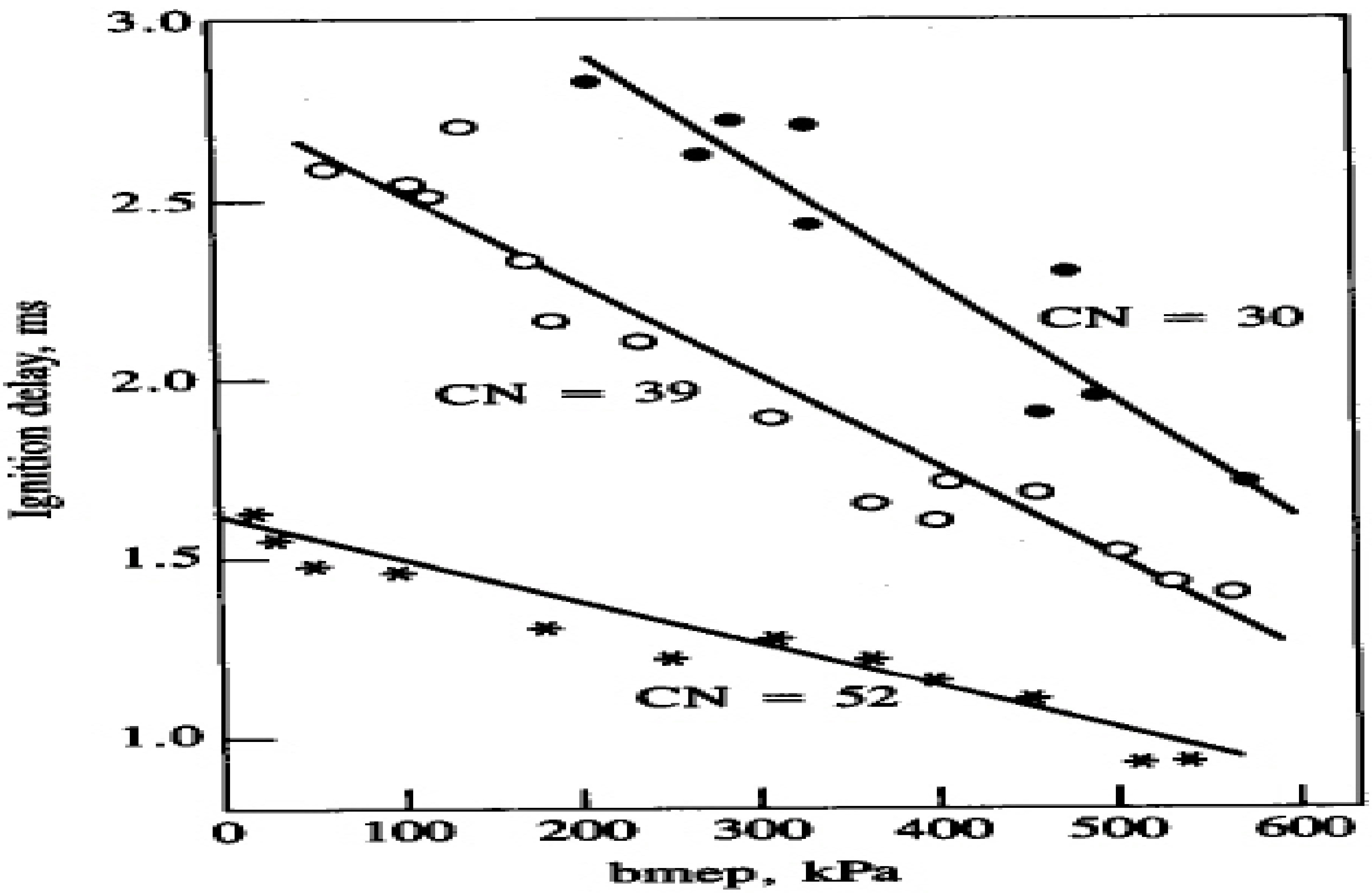
•Earlier or later injection timing results in a lower air temperature and pressure during the delay period → increase in the ignition delay time.

•*<u>Injection quantity</u>* – For a CI engine the air is not throttled so the load is varied by changing the amount of fuel injected.

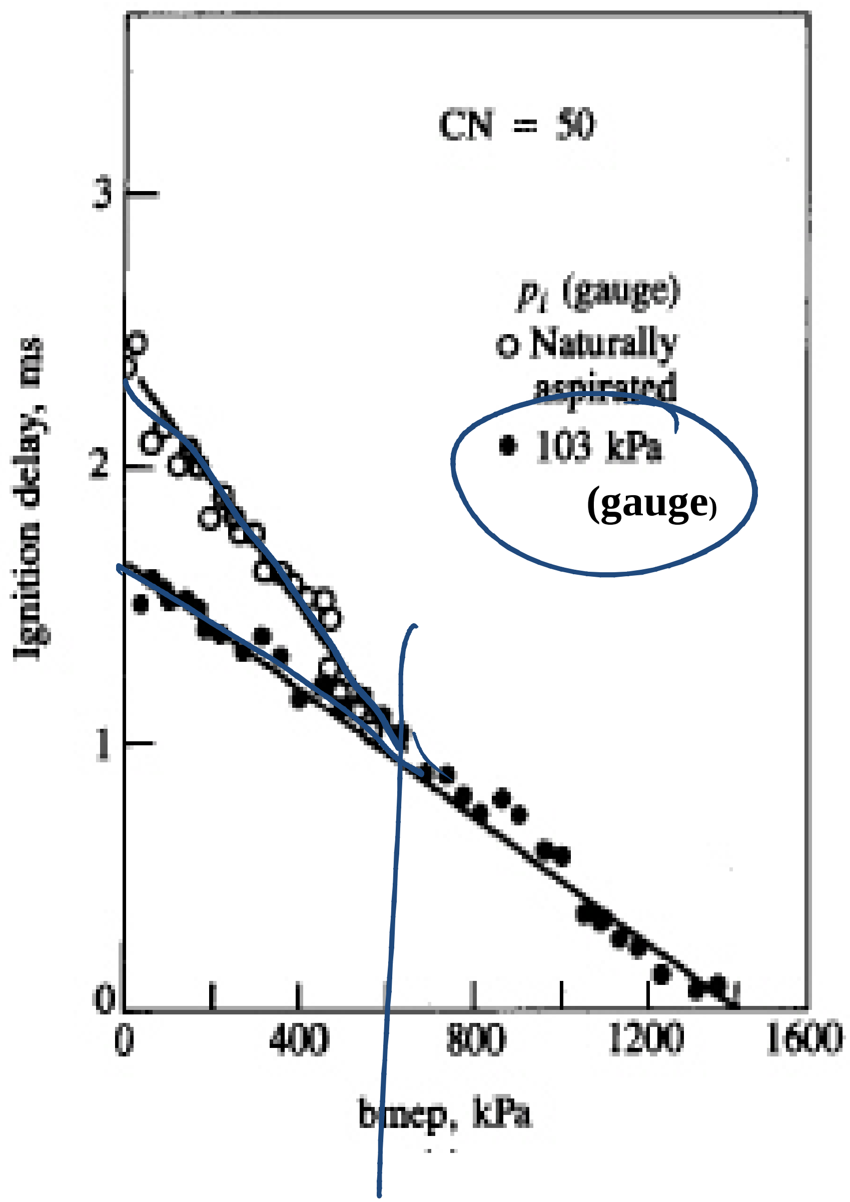
•Increasing the load (bmep) increases the residual gas and wall temperature which results in a higher charge temperature at injection → decrease in the ignition delay.

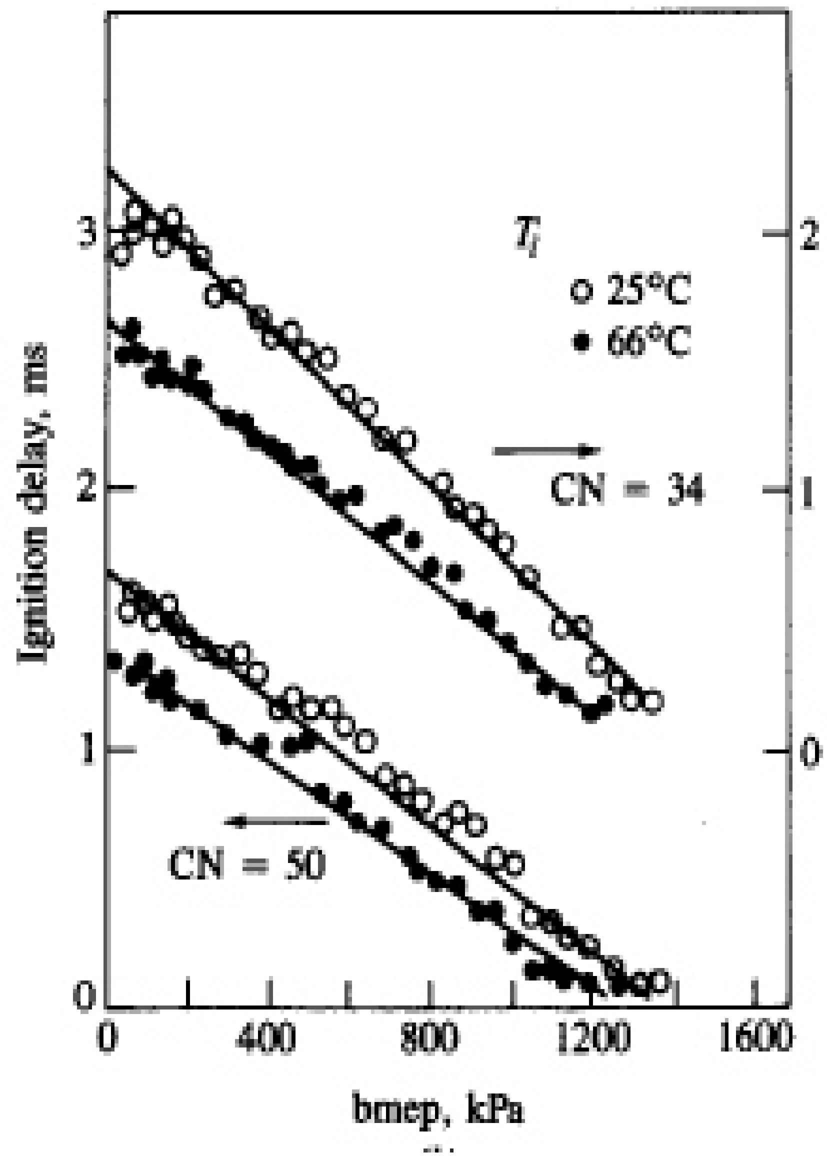
•*<u>Intake air temperature and pressure</u>* – an increase in ether will result in a decrease in the ignition delay, an increase in the compression ratio has thesame effect.

Thermodynamic Factors Affecting Ignition Delay



Thermodynamic Factors Affecting Ignition Delay



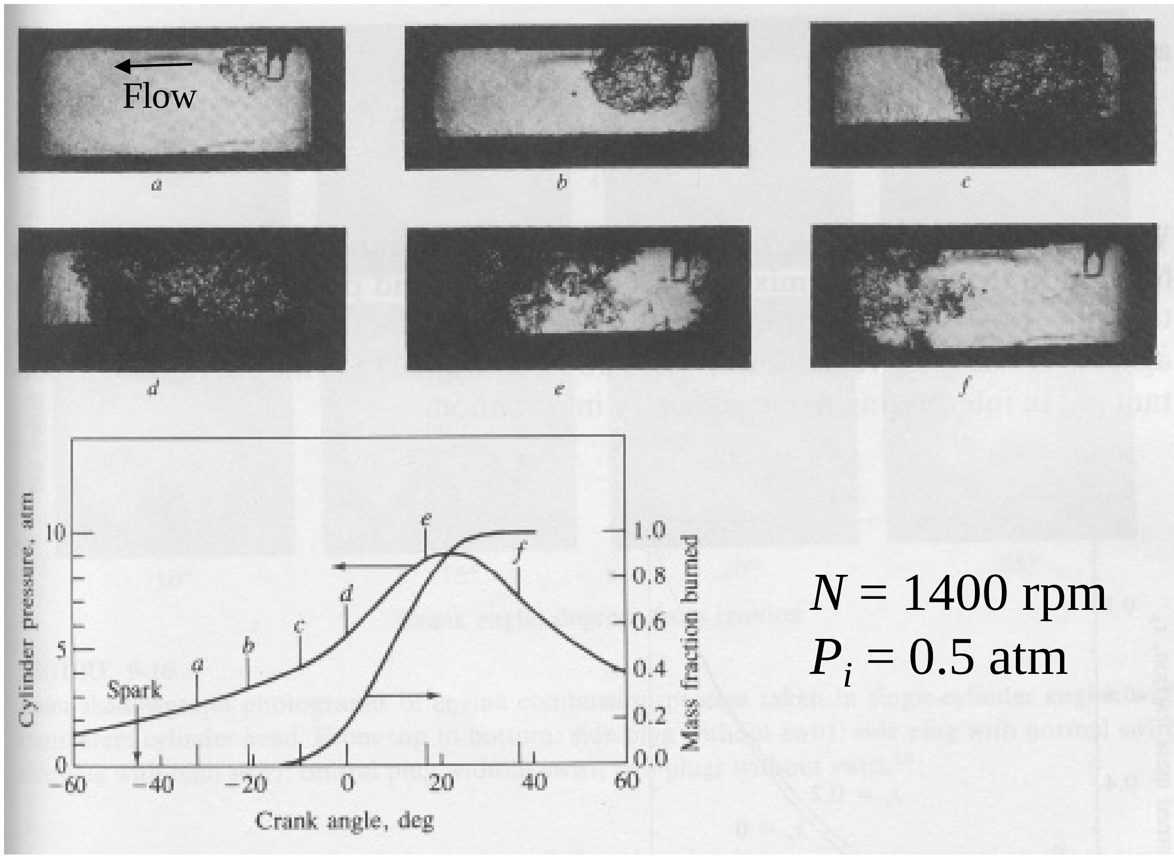


SI ENGINES

Flame Propagation in SI Engine

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

The turbulent flame spreads away from the spark discharge location.



N = 1400 rpm

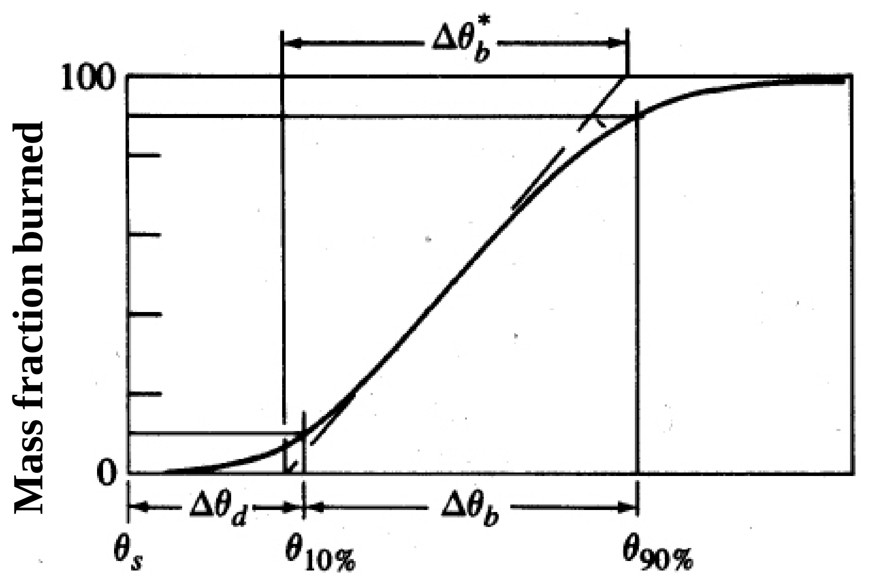
P_i = 0.5 atm

Flame Development

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

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

Overall burning angle - sum of flame development and rapid burning angles



Mixture Burn Time vs Engine Speed

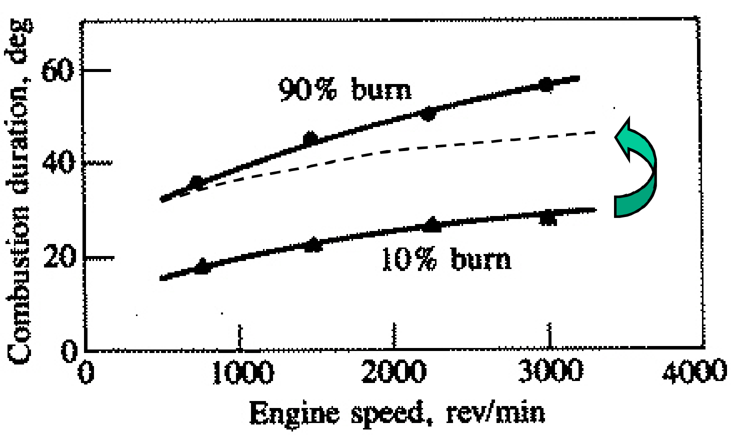
How does the flame burn all the mixture in the cylinder at high engine speeds?

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

Recall the turbulent intensity increases with piston speed, $u_t = ½\, u_p$

Recall the turbulent burning velocity is proportional to the turbulent intensity $S_t \sim u_t$, so at higher engine speeds the turbulent flame velocity is also higher and as a result need less time to burn the entire mixture

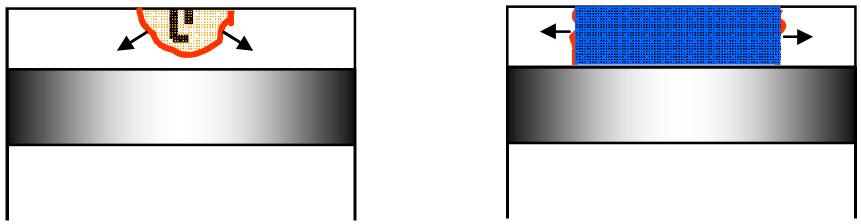
Combustion duration in crank angles (40-60 degrees) only increases a small amount with increasing engine speed.



$\phi = 1.0$
P_i =0.54 atm
Spark 30º 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

a) laminar burning velocity, or

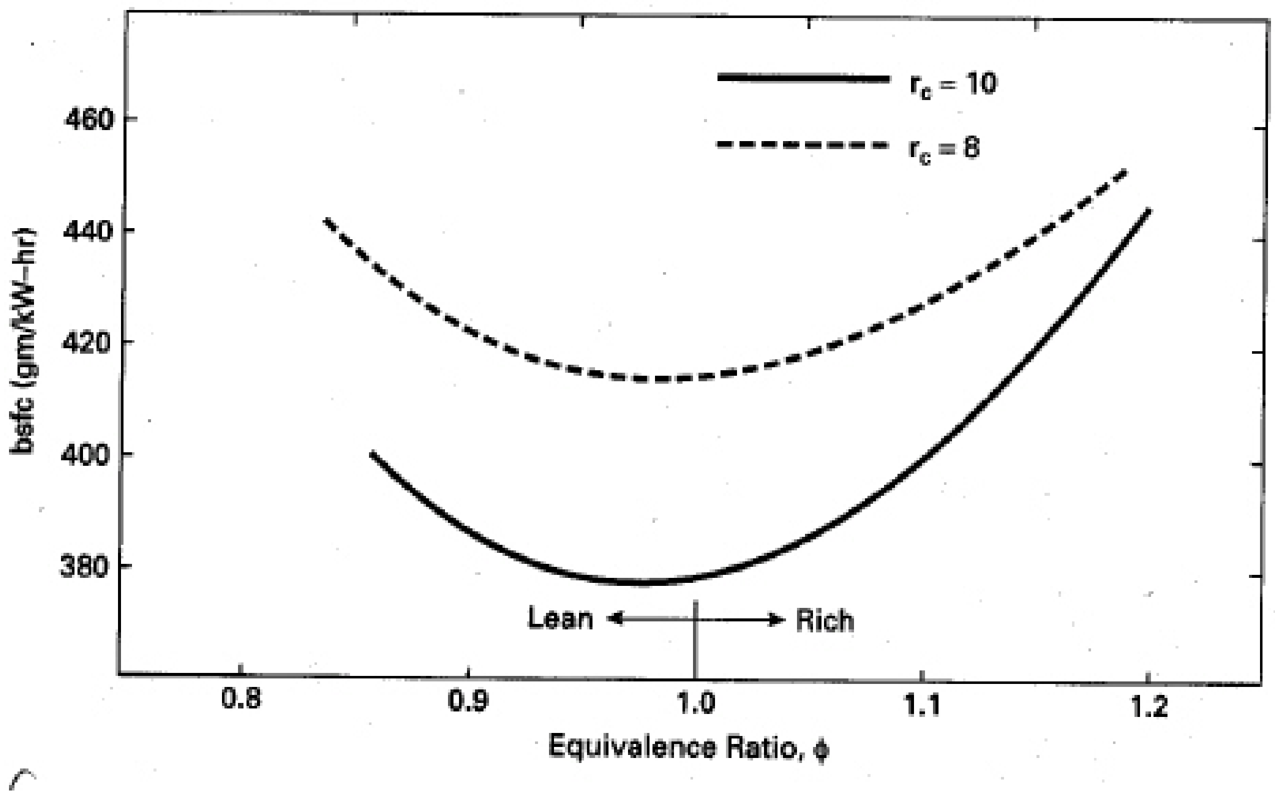
b) turbulence intensity.

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

Optimum F/A Composition

Maximum power is obtained for a F/A that is about 1.1 since this gives the highest burning velocity and thus minimum heat loss.

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

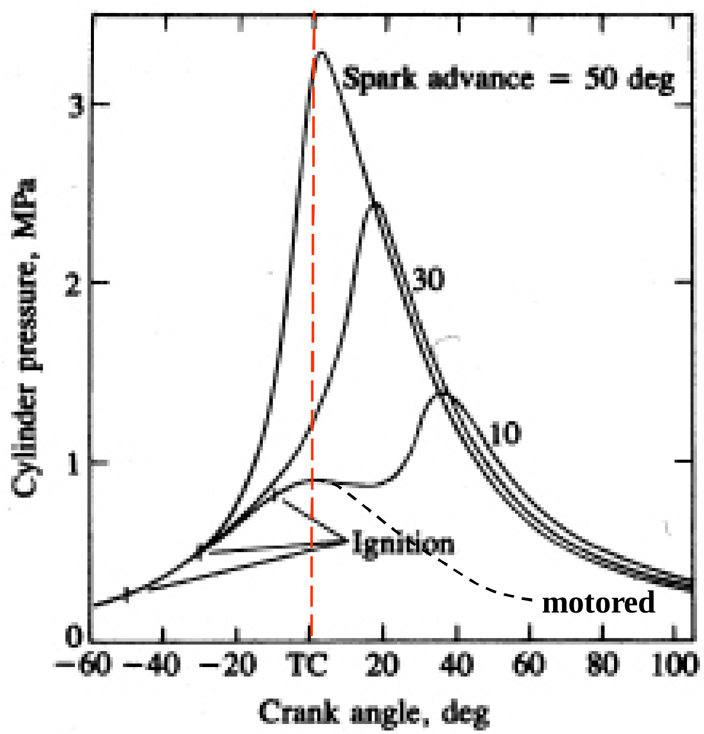


Spark Timing

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

Want to ignite the gas before TC so as to center the combustion around TC.

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



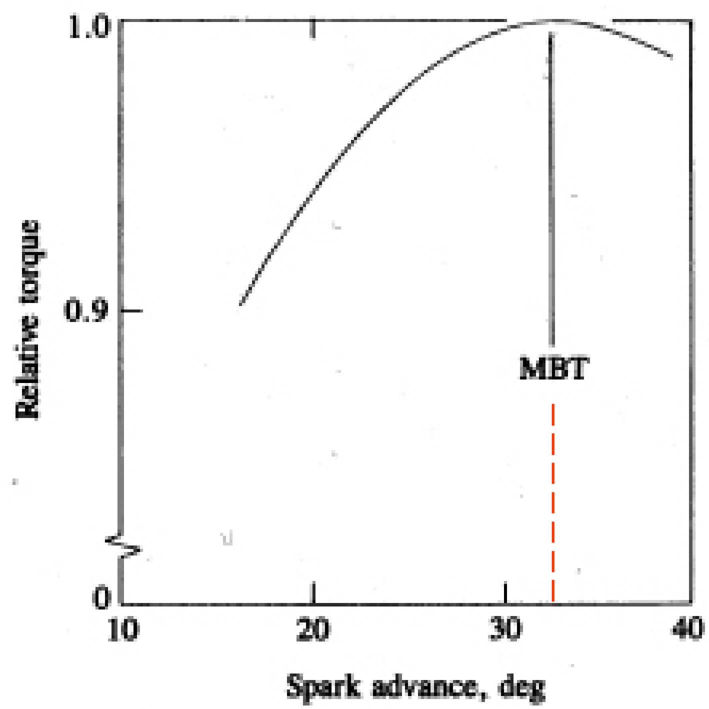
Engine at WOT, constant engine speed and A/F

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.

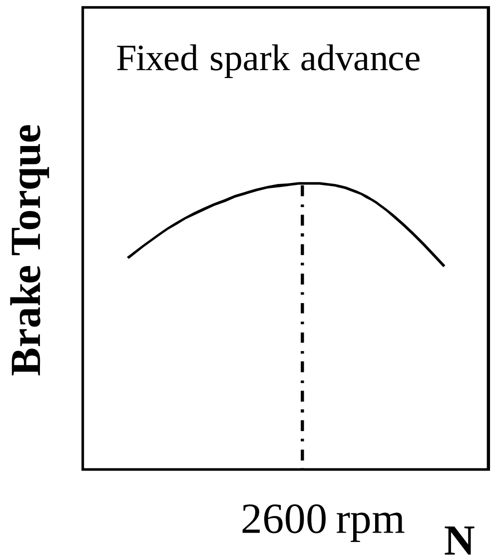
The optimum spark timing which gives the maximum brake torque, called **MBT timing** occurs when these two opposite factors cancel.

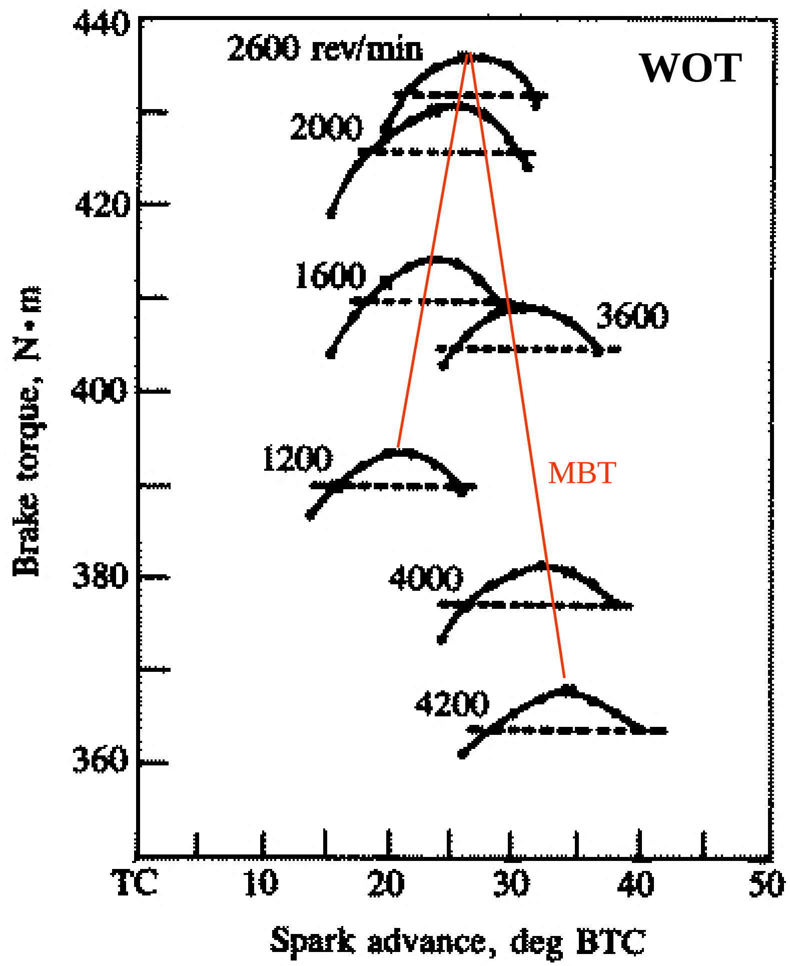
Engine at WOT, constant engine speed and A/F



Effect of Engine Speed on Spark Timing

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

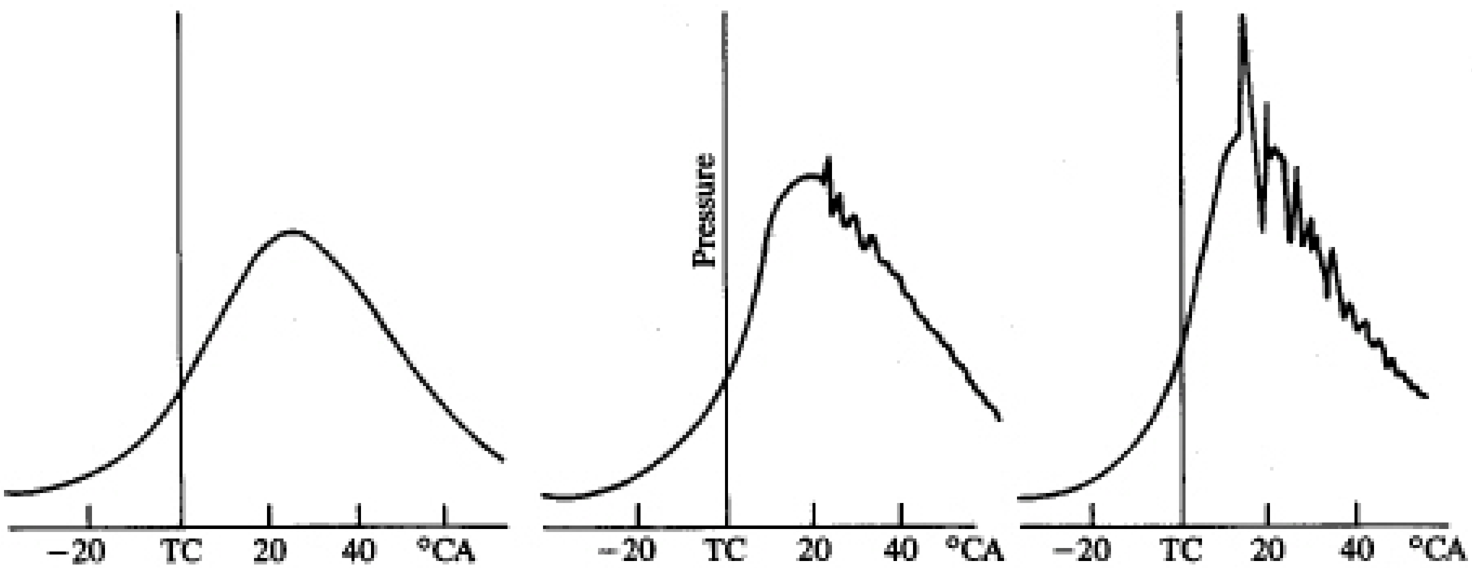




Abnormal Combustion in SI Engine

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

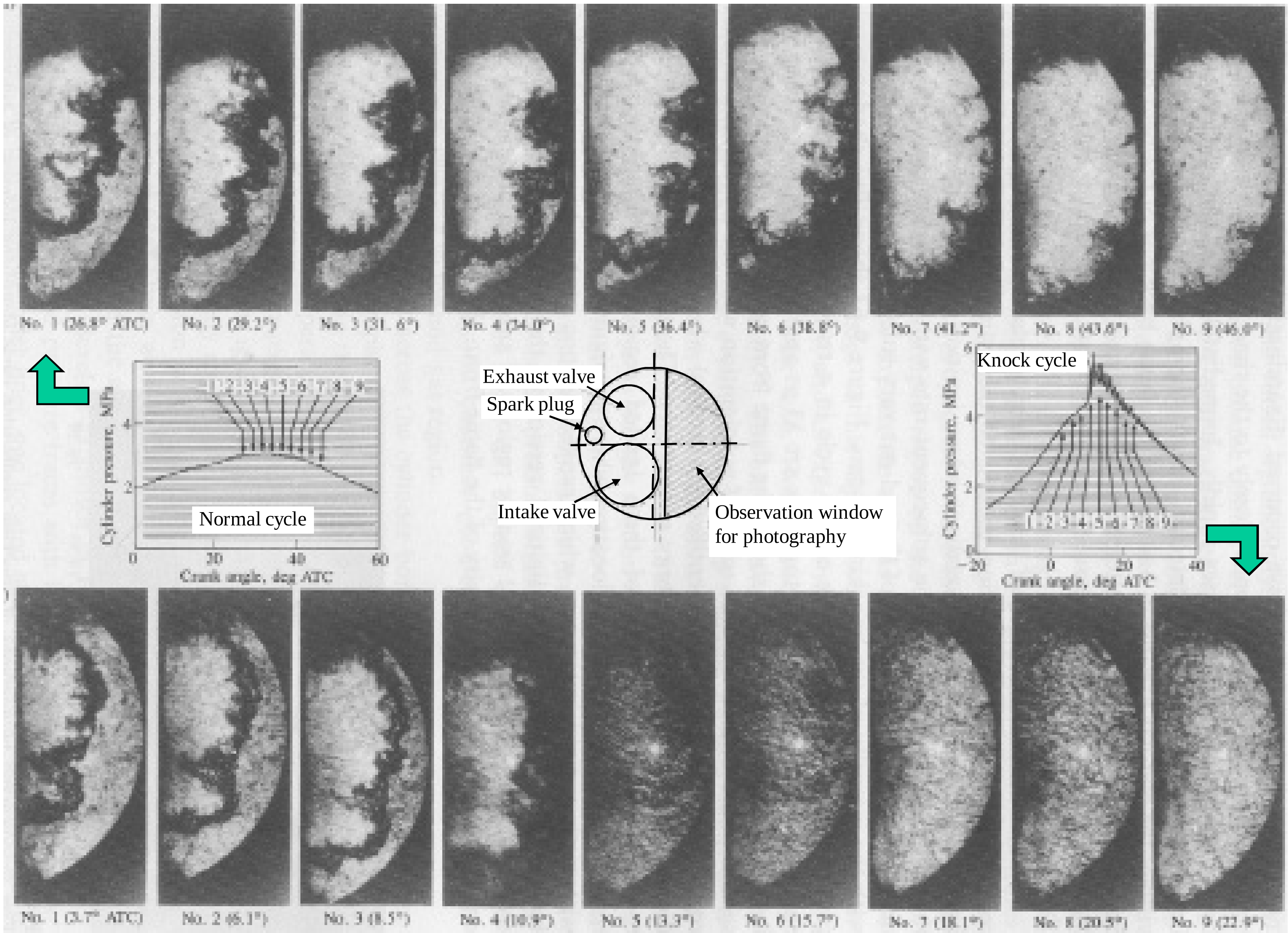
The noise is generated by shock waves produced in the cylinder when unburned gas ahead of the flame auto-ignites.



(*a*) Normal combustion, spark 28°BTC

(*b*) Slight knock, spark 28°BTC

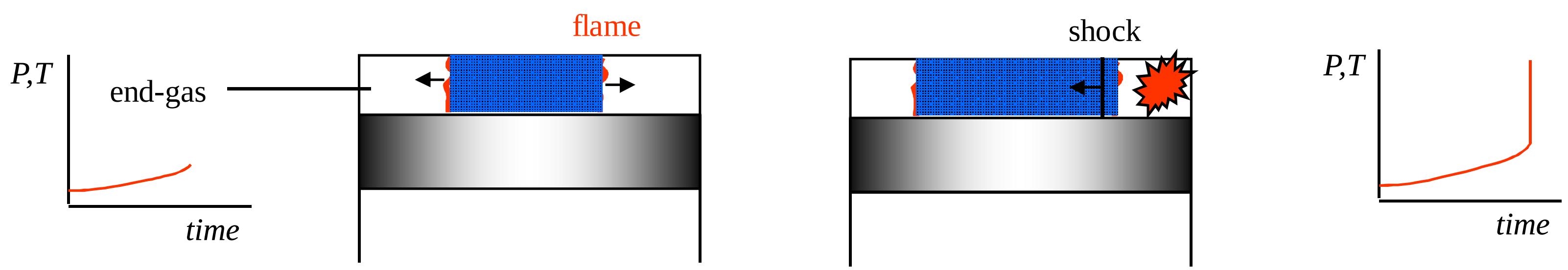
(*c*) Intense knock, spark 32°BTC


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 (46.0°)
Normal cycle
Cylinder pressure, MPa
Crank angle, deg ATC
Exhaust valve
Spark plug
Intake valve
Observation window for photography
Knock cycle
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 (22.9°)

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 autoignite and burn very rapidly producing a shock wave



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 in the end-gas can occur then knock is avoided.

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

Parameters Influencing Knock

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

ii) *Engine speed* – 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.

iii) *Spark timing* – maximum compression from the piston advance occurs at TC, 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.

Fuel Knock Scale

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

The octane number determines whether or not a fuel will knock in a given engine under given operating conditions.

By definition, normal heptane (n-C_7H_{16}) has an octane value of zero and isooctane (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% isooctane has an octane number of 90.

A fuel's octane number is determined by measuring what blend of these two hydrocarbons matches the test fuel's knock resistance.

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 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.

	Research	Motor
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 isooctane.

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 a magnetostriction knock detector.

• 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 stand.

The antiknock index which is displayed at the fuel pump :

$$Antiknock\ index = \frac{RON + MON}{2}$$

Note the motor octane number is always higher because it uses more severe operating conditions: 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.

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

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).

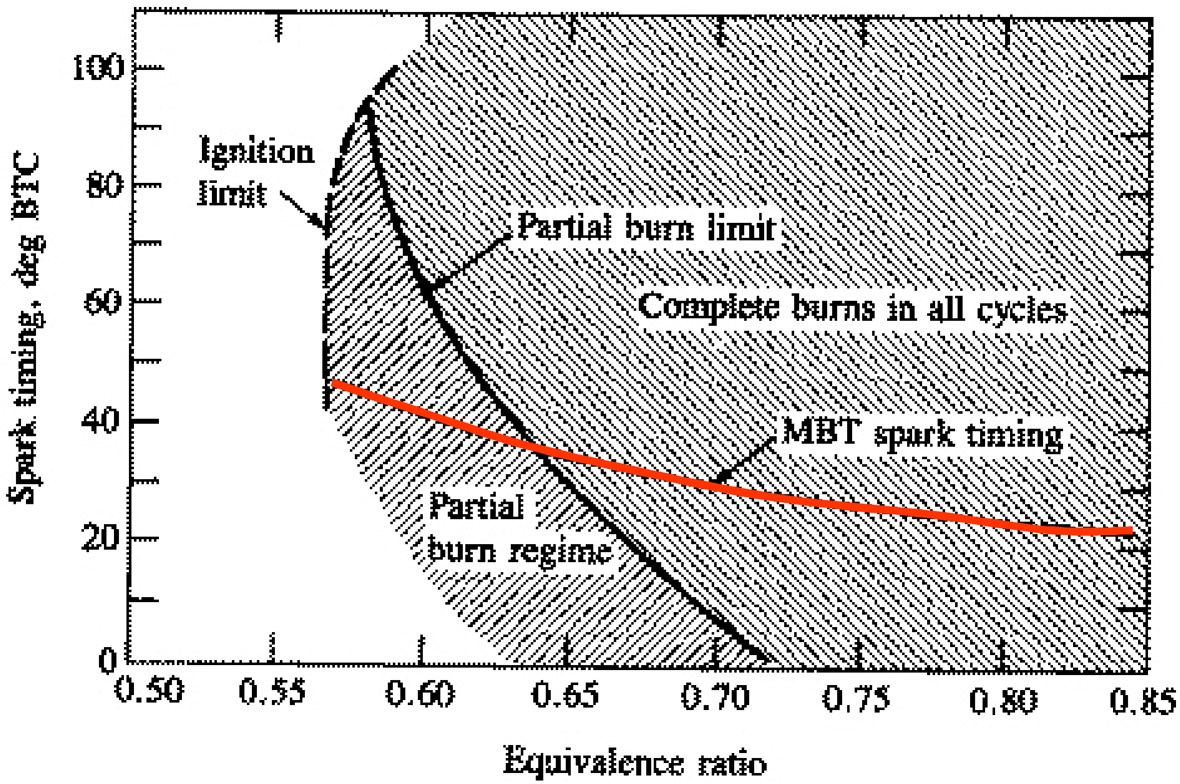
Alcohols such as ethanol and methanol have high knock resistance.

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).

Effect of Fuel-air Dilution

Set spark timing for maximum brake torque (MBT), leaner mixture needs more spark advance since burn time longer.

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



Alternative Fuels

What is there besides gasoline?

[redacted]

[redacted]

Biodiesel

What is Biodiesel?

• Biodiesel is a fuel made from vegetable oil, animal fats, and used restaurant grease

Why is a good alternative to traditional fuels?

• Lower emissions

• Renewable

• Little/no engine modification

• Can be blended with traditional fuel

• Biodegradable

• Infrastructure exists

How can Biodiesel help the environment?

- In a blended state with traditional fuel it can lower emissions such as a 20% blend lowers CO_2 emissions by 15%
- 100% Biodiesel can lower CO_2 emissions by 75%
- Biodiesel produces fewer particulate matter, carbon monoxide, and sulfur dioxide emissions
- It’s safe to store, handle, and transport cause of a high flash point of 150 degrees Celsius instead of 77 degrees Celsius for traditional fuels.

Is Biodiesel practical?

- Yes, it uses the current infrastructure and technology and costs $1 to $1.50 per gallon

Electricity

How is it used as fuel?

• Electricity is used as fuel in the form of batteries and fuel cells.

Are they practical?

• Batteries are a source of power but have limited range and require frequent charging and are more suited to short range community use

• Fuel Cells are more promising because they use other fuels to create the electrical energy

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Hydrogen

What are some cons?

- When the public thinks of hydrogen, the explosion of the famous Hindenburg airship and this makes for low public opinion
- Hydrogen is extremely reactive with oxygen and makes it highly flammable
- Because of hydrogen’s reactive nature, concept hydrogen cars have/are going through many crash tests and results are good

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Propane

What is propane?

- Propane is a liquefied gas made up of propane, propylene, butane, and butylene from petroleum

What are the benefits?

- A 98% reduction in toxic emissions in light-duty bi-fuel vehicles
- In the quantities needed it costs less than gasoline
- Very accessible compared to other alternative fuels (4,000 publicly accessible facilities in the US)

Propane

What does the future hold?

• Currently 200,000 vehicles in the US use propane (mostly fleet vehicles like taxis and police cars)

• Since the current infrastructure can easily be converted to dispense propane it makes for a cost effective solution to gasoline by using the current fuel dispensing system

P-Series

What is P-Series?

• It is a colorless fuel made of natural gas liquids, ethanol, and methyltetrahydrofuran

Where is it used?

• P-Series fuels are primarily used in flexible fuel vehicle in a pure form or mixed with other fuels

• This type of fuel is not widely produced or used like some of the other fuels