Fuel & Advanced Combustion

Lecture 1
Fuel

Fuels

- Since the heat energy is derived from the fuel, a fundamental knowledge of the types of fuels and their characteristics is essential to understand the combustion phenomenon.

- The characteristics of fuel has a considerable influence on the design, efficiency, output and particularly the reliability and durability of the engine.

- Further, the fuel characteristics play an important role in the atmospheric pollution caused by the automobile engines.

Fuels

- Internal combustion engines can be operated on different types of fuels such as
  - Liquid fuels
  - Gaseous fuels
  - Solid fuels

- The design of the engine usually depends upon the type of fuel used.

Solid Fuels

- This type of fuel was used in early engines. During the initial stages of engine development, solid fuels (such as finely powdered coal) was used.

- However, due to the problem of handling the fuel as well as in disposing off the solid residue or ash (after combustion), solid fuels find little practical application today.

Solid Fuels – contd.

- Further, there are storage and feeding problems associated with solid fuels as compared to gaseous and liquid fuels.

- However, attempts are being made to produce gaseous or liquid fuels from charcoal for their use in engines.

Gaseous Fuels

- Gaseous fuels are ideal for internal combustion engines. They mix more homogeneously with air. However, their use is restricted in automobiles due their storage and handling problems.

- Gaseous fuels are suitable for stationary powerplants near the source of availability of the fuel. They can be liquefied under pressure to reduce the storage volume, but this process is very expensive and risky.

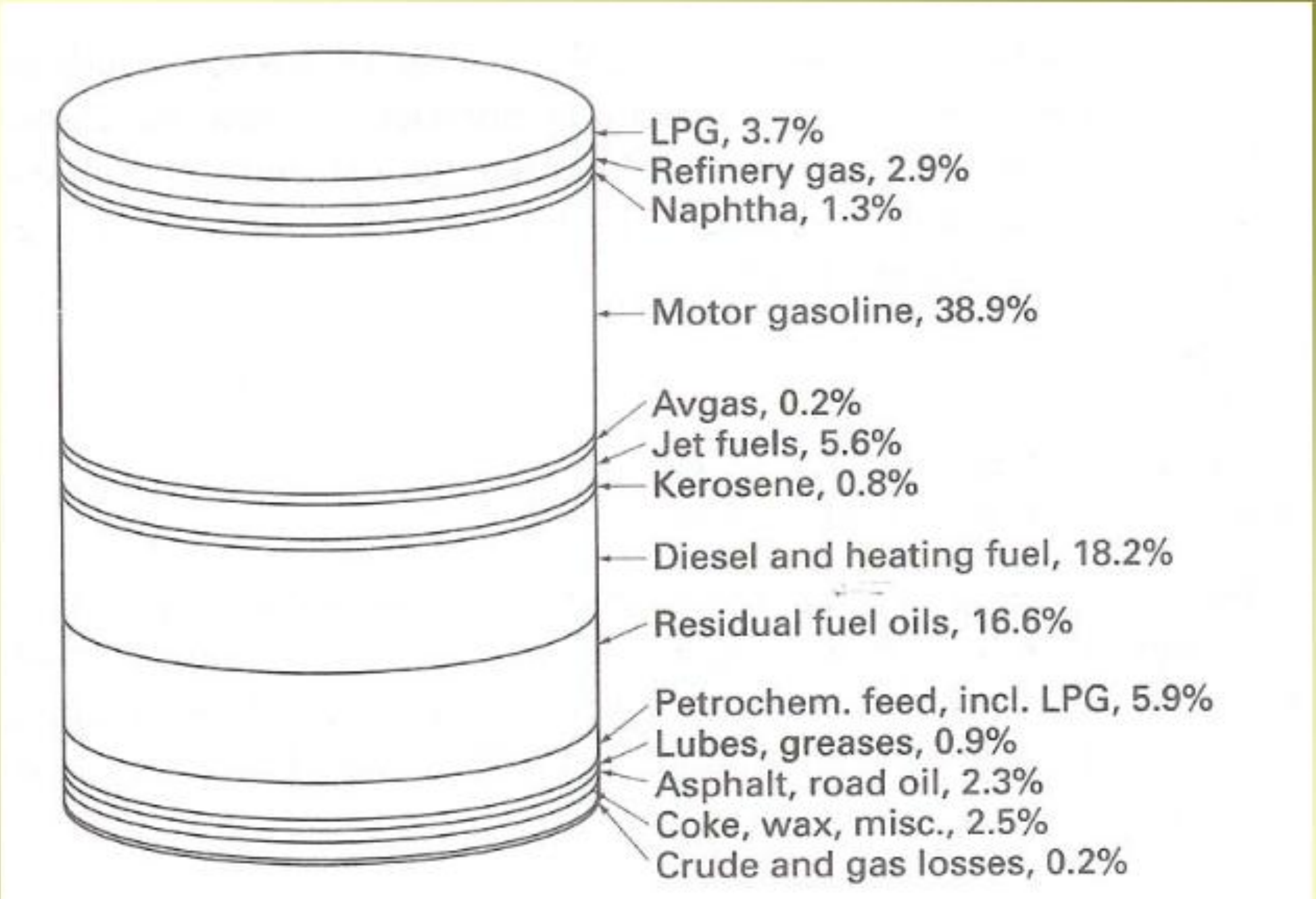
Liquid Fuels

- The liquid fuels are mostly used in modern internal combustion engines. Basically, they are the derivatives of liquid petroleum. The commercial types are:

  - Benzyl
  - Alcohol
  - Petroleum products

Petroleum

- Petroleum (obtained from crude oil) is a mixture of many hydrocarbons with varying molecular structure. It also contains small amounts of
  - Sulphur
  - Oxygen
  - Nitrogen
  - Impurities (such as water, sand etc.)



Typical end products from crude oil. A single refinery produces some, but not all, of the products shown. The percentage refer to overall production from total refinery output.

Petroleum

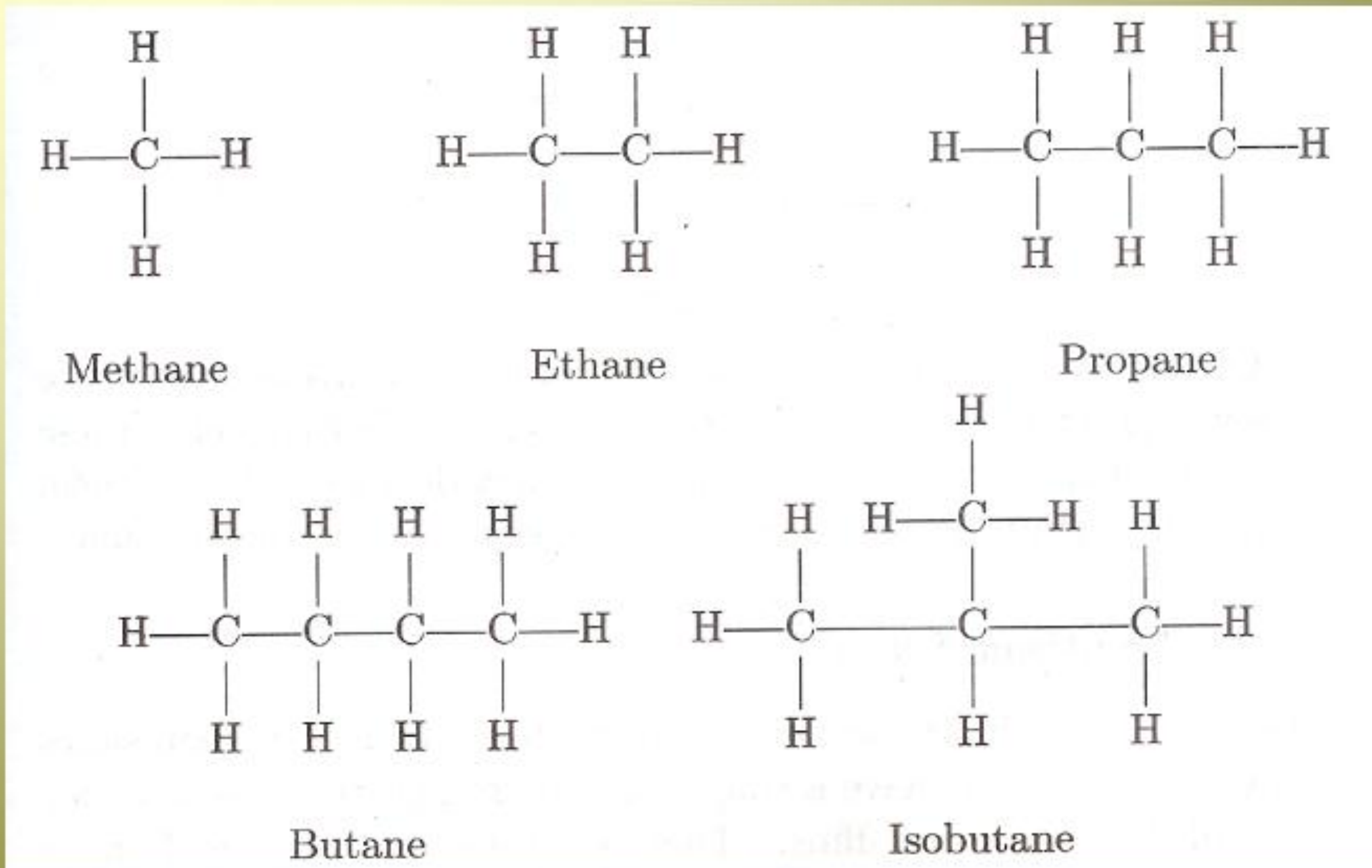
- The linking of hydrogen and carbon atoms (in different ways in a hydrocarbon molecule) influences the physical and chemical properties of different hydrocarbon groups.

- The carbon and hydrogen combine in different proportions and molecular structures to form a variety of hydrocarbons. Depending upon the number of carbon and hydrogen atoms, the petroleum products are classified into various groups.

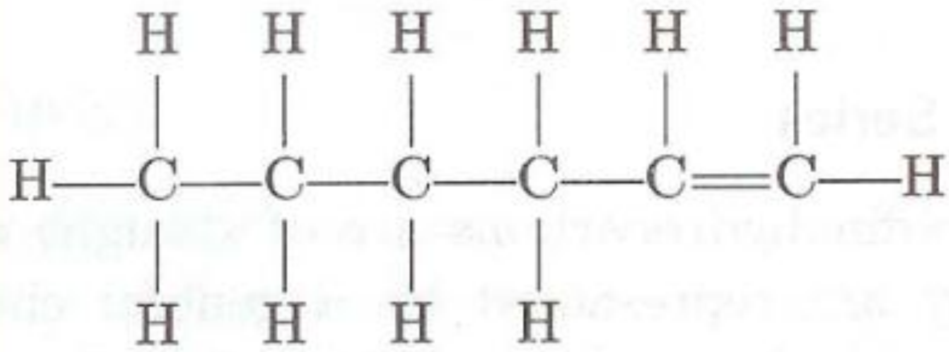
Basic families of hydrocarbons

Family of hydrocarbons	General formula	Molecular structure	Saturated/ Unsaturated	Stability
Paraffin	C_nH_{2n+2}	Chain	Saturated	Stable
Olefin	C_nH_{2n}	Chain	Unsaturated	Unstable
Naphthene	C_nH_{2n}	Ring	Saturated	Stable
Aromatic	C_nH_{2n-6}	Ring	Highly unsaturated	Most unstable

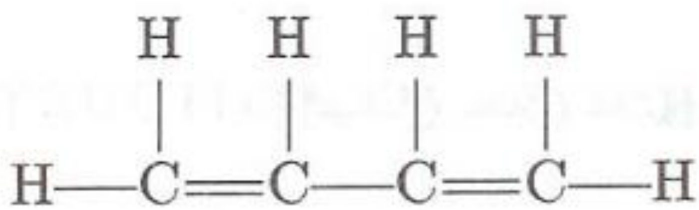
Paraffin series



Olefin series



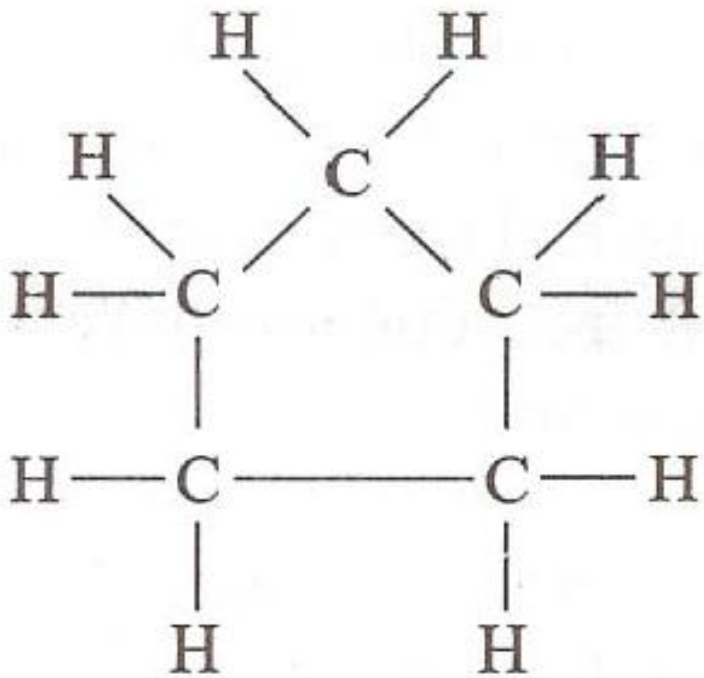
Hexene



Butadiene

Remark: ***Unsaturated as they contain one or more double bonds between carbon atoms.***

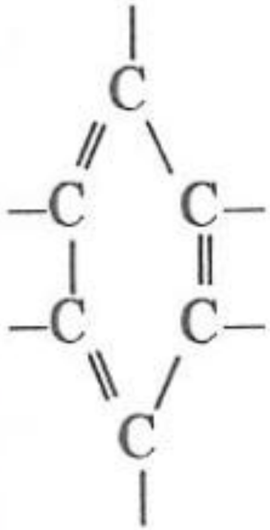
Naphthene series



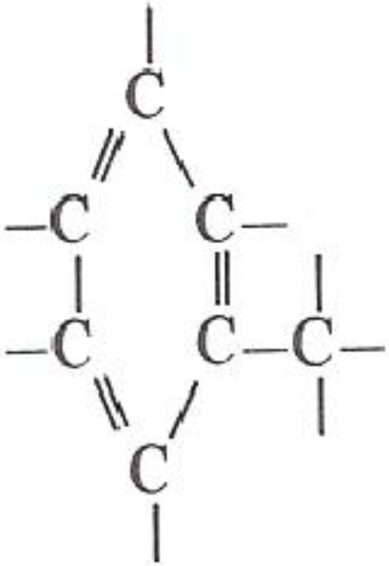
Cyclopentane

Remark: ***Have a Ring Structure; Saturated and Stable.***

Aromatic series



Benzene, C_6H_6



Toluene, $C_6H_5CH_3$

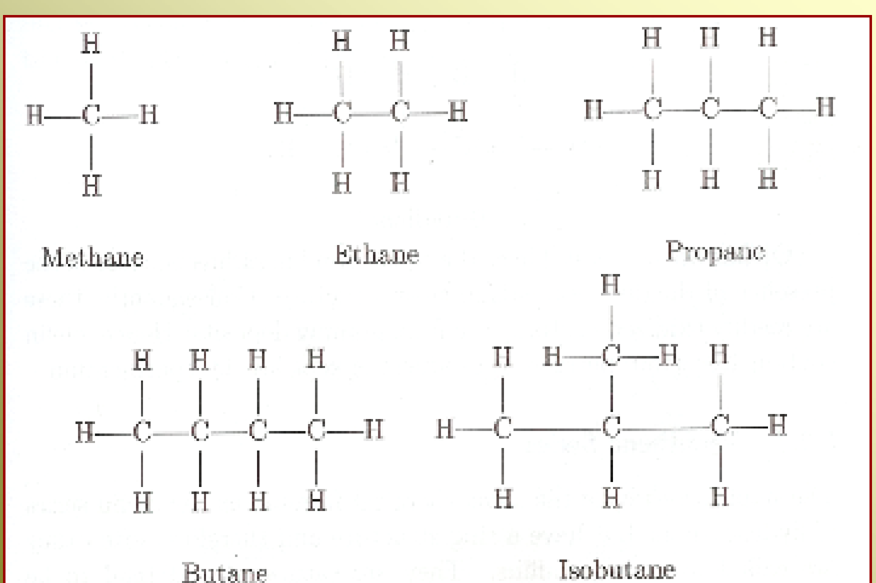
Remark:* *Unsaturated Ring Structure with double carbon-carbon bonds.

Aromatics

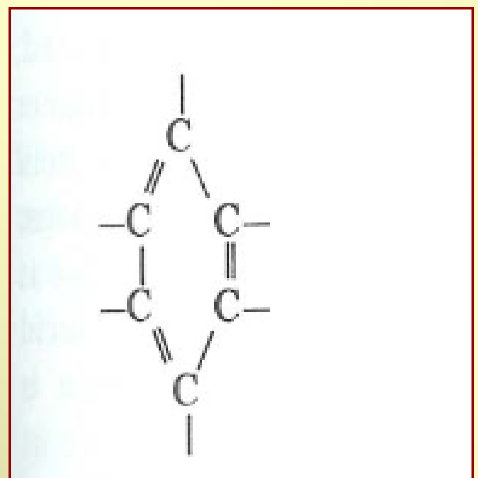
- Aromatics generally make good gasoline fuel. They have high densities in the liquid state and thus have high energy content per unit volume. Aromatics will dissolve a greater amount of water than some other hydrocarbons. This can create fuel line freezing problems when temperature is lowered and some of the water comes out of solution. Aromatics make poor CI engine fuel.

General Remark

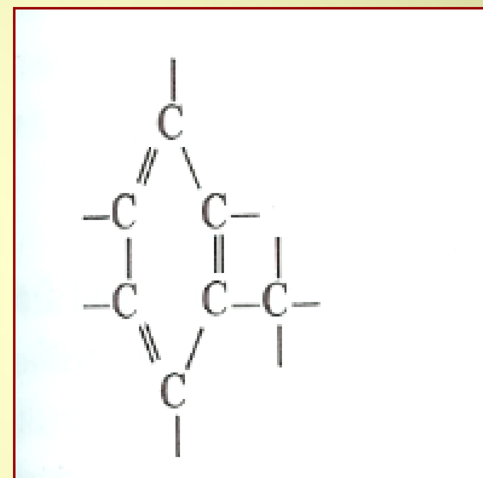
- Antiknock quality improves with increasing no. of carbon atoms and the compactness of molecular structure. Normal paraffins exhibit the poorest antiknock quality when used in SI engine. The aromatics offer the best resistance to knocking in SI engines. For CI engines, normal paraffins are the best fuels.



Methane, Ethane, Propane, Butane, Isobutane



Benzene, C_6H_6



Toluene, $C_6H_5CH_3$

General Remark

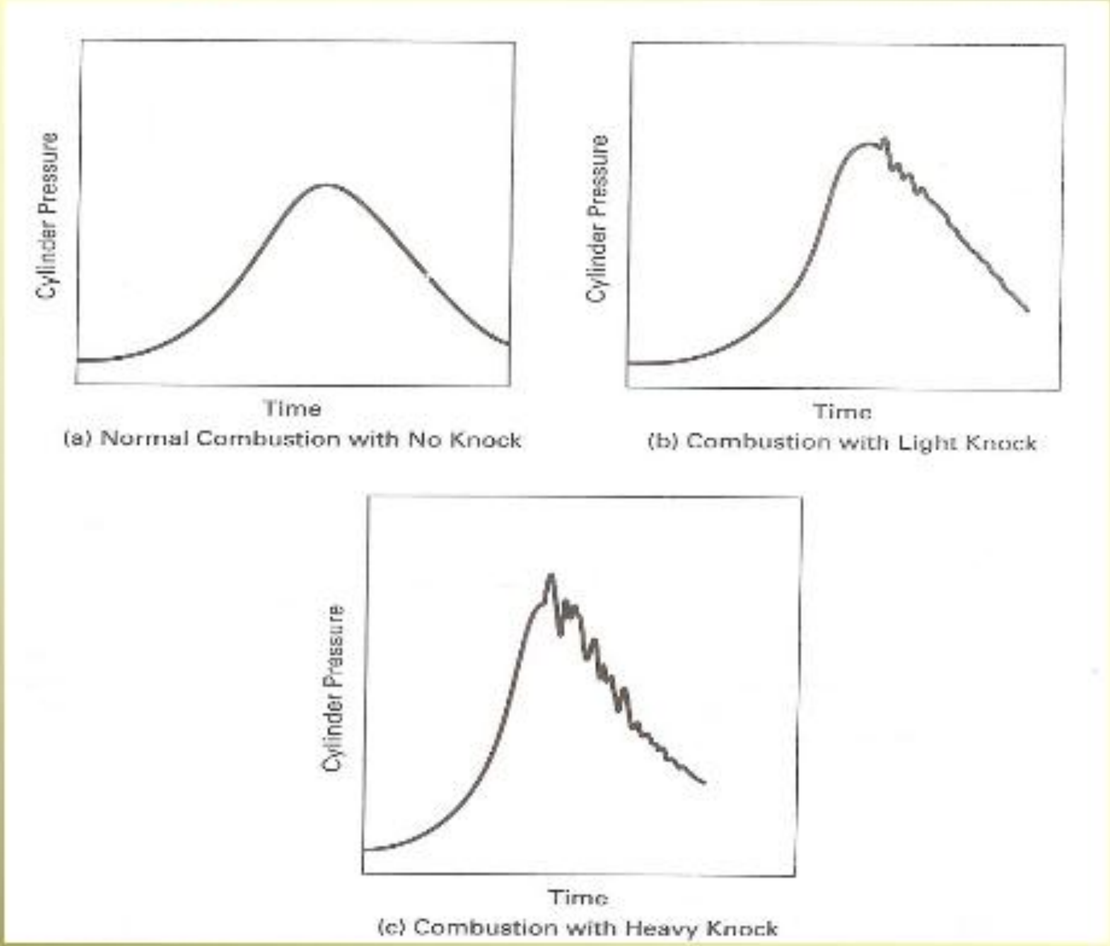
- As the number of atoms in the molecular structure increases, boiling temperature increases. Hence, the fuels with lesser atoms in the molecule are more volatile.

- The heating value increases with increased number of hydrogen atoms in a molecule. Therefore, paraffins have the highest heating value, and the aromatics the least.

Antiknock Quality

- Abnormal burning/detonation in SI engine causes a very high rate of energy release, temperature and pressure. This adversely affects the thermal efficiency. The fuel characteristics should resist this tendency. This property of fuel is called its antiknock quality.

❑ **With no self-ignition, the pressure force on piston follows a smooth curve, resulting in smooth engine operation. When self-ignition occurs, pressure forces on piston are not smooth and engine knock occurs.**



Rating of Fuels

- Fuels are rated for their antiknock qualities.
  - Gasoline : Octane number
  - Diesel : Cetane number

- Resistance to knock depends upon the chemical composition of fuel (or characteristics of hydrocarbon in the fuel).

- Other operating parameters:
  - F-A ratio
  - Ignition timing
  - Engine speed
  - Shape of combustion chamber
  - Compression ratio etc.

SI Engine Fuels

- **Antiknock property is compared with reference to**
  - iso-octane (C_8H_{18}) $\Rightarrow$ 100 Octane No.
  - heptane (C_7H_{16}) $\Rightarrow$ Zero Octane No.

Very poor antiknock fuel

Very good antiknock fuel

- **Fuel with Octane Number of 70 indicates**
  - 70 % octane, and
  - 30 % heptane

Octane Number (ON)

- **Definition:** It indicates the % by volume of iso-octane in a mixture of iso-octane and heptane which exhibit the same characteristics of the fuel in a standard engine under a set of operating conditions.

- Common octane numbers for gasoline fuels used in automobile range from 87 to 95, with higher values for special high performance and racing cars.

Tests for Rating Octane Number (ON)

- Two most common methods of rating gasoline and other SI engine fuels are the Motor Method and the Research Method. These give the motor octane number (MON) and research octane number (RON).

- Another less common method is the Aviation Method used for aircraft fuel, and this gives an Aviation Octane Number (AON).

Tests for Rating ON

- ❑ **The engine used to measure MON and RON was developed in 1930s. It is a single-cylinder, OHV engine that operates on four-stroke Otto cycle with variable compression ratio (3 to 30). Test conditions to measure MON and RON are shown below.**

TABLE 4-3 TEST CONDITIONS FOR OCTANE NUMBER MEASUREMENT

	RON	MON
Engine Speed (RPM):	600	900
Inlet Air Temperature (°C):	52 (125°F)	149 (300°F)
Coolant Temperature (°C):	100 (212°F)	100
Oil Temperature (°C):	57 (135°F)	57
Ignition Timing:	13° bTDC	19°–26° bTDC
Spark Plug Gap (mm):	0.508 (0.020 in.)	0.508
Inlet Air Pressure:	atmospheric pressure	
Air–Fuel Ratio:	adjusted for maximum knock	
Compression Ratio:	adjusted to get standard knock	

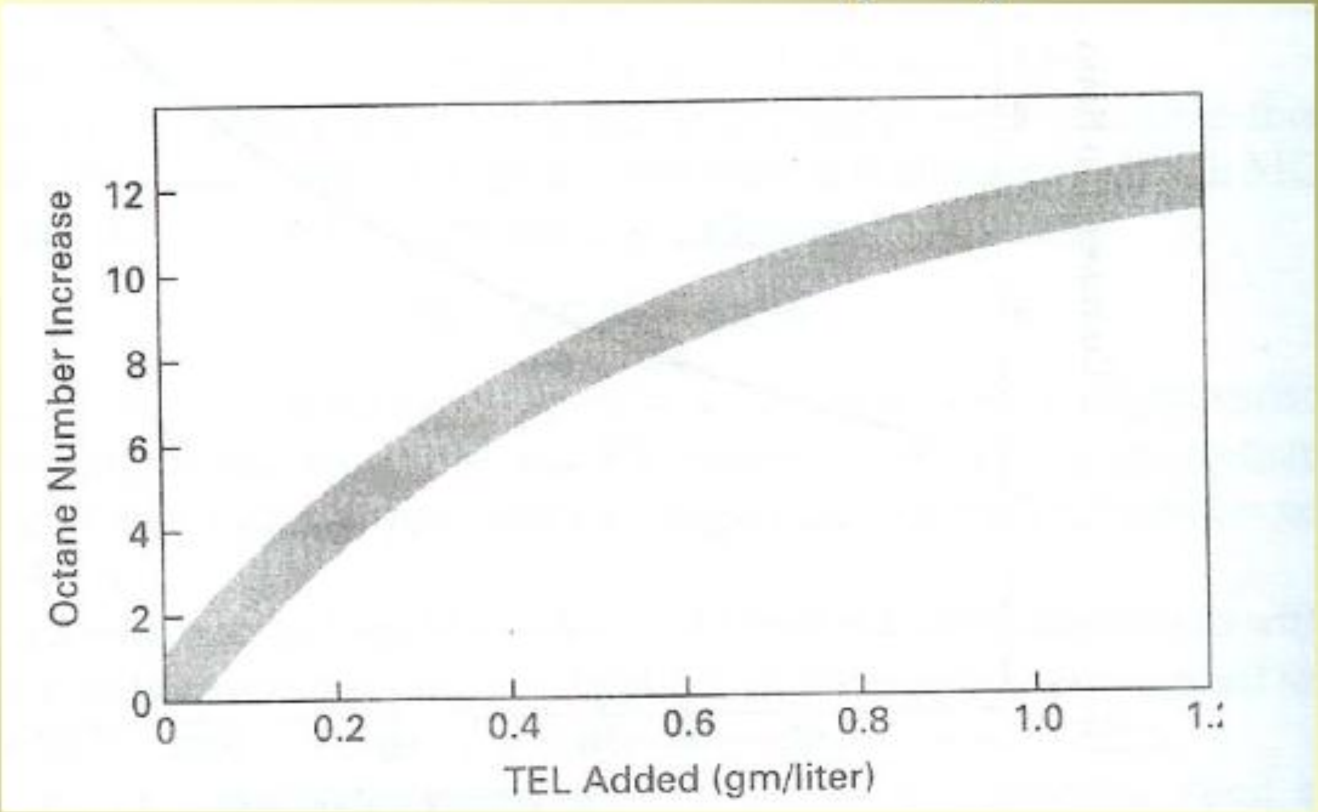
Adapted from [58].

Tests Procedure

- The test engine is run at specified conditions using the fuel being tested. Compression ratio is varied until a standard level of knock is experienced. The test fuel is then replaced with a mixture of two standard fuels.

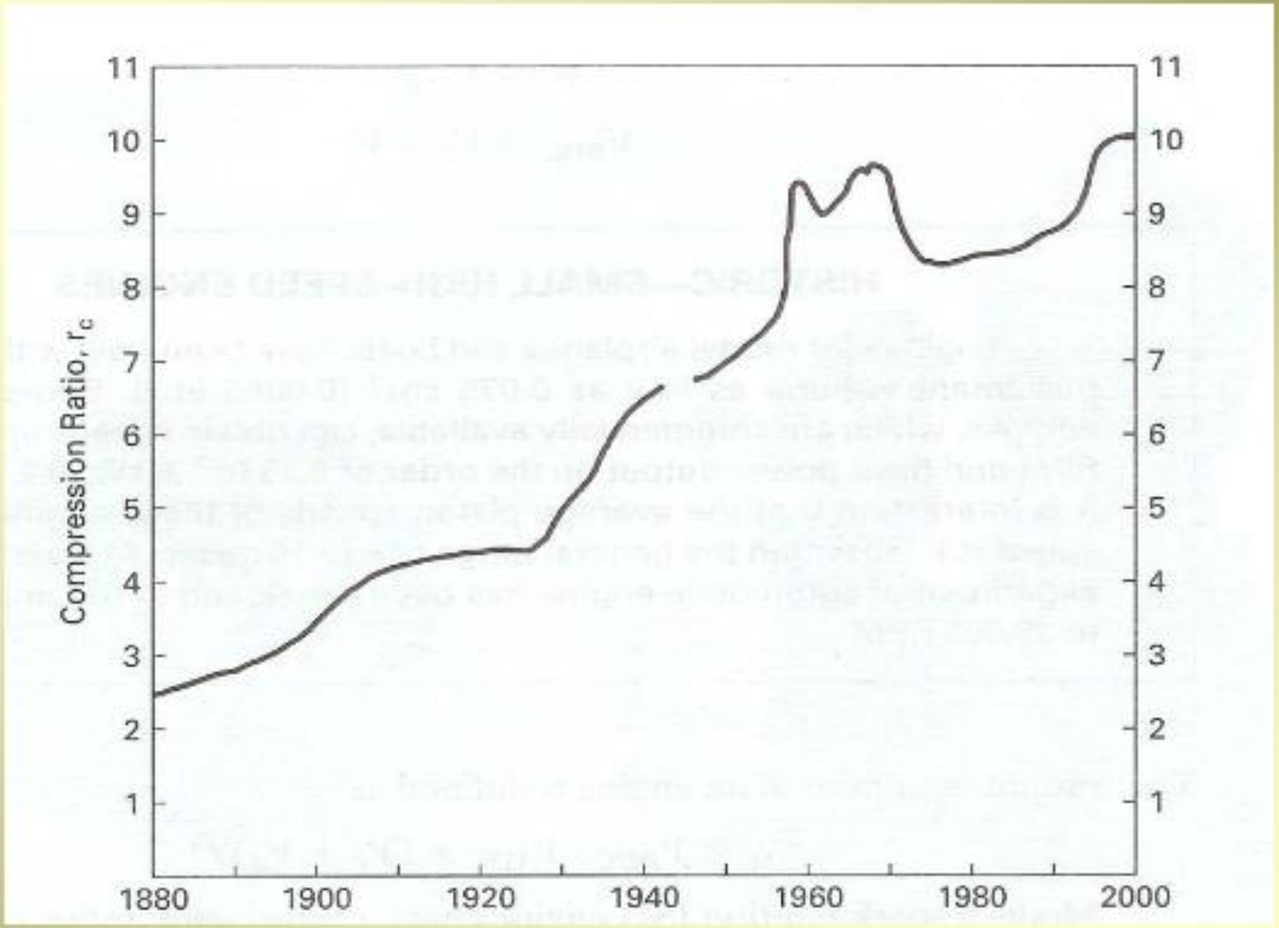
- The intake system of the engine is designed such that the blend of two standard fuels can be varied to any percent *(from all isooctane to all n-heptane)*. The blend of fuels is varied until the same knock characteristics are observed as with the test fuel. The percent of isooctane in the fuel blend is the ON given to the test fuel.

Octane Number (ON)



- There are a number of gasoline additives that are used to raise the octane number. For many years, the standard additive was tetraethyl lead (TEL). A few millilitres of TEL in several litres of gasoline could raise the ON several points.

Octane Number (ON)



- The above figures shows how the compression ratios of automobile engines increased after the introduction of TEL in the 1920s.

Gasoline additives

Additives	Type	Function
Oxidation inhibitors	Aromatic amines and phenols	Inhibit gum formation and oxidation
Corrosion inhibitors	Carboxylic acids and carboxylates	Inhibit corrosion of ferrous metals
Metal deactivators	Chelating agent	Inhibit gum formation Catalyzed by certain metals
Anti-icing additives	Surfactants and glycols	Prevent icing in carburetor and fuel system
Detergents	Amines and amine carboxylates	Prevent deposits in carburetor throttle body
Deposit control additives	Polybutene amines Polyether amines	Remove and prevent deposits throughout carburetor intake ports and valves
Blending agents	Ethanol, methanol, tertiary butyl alcohol, methyl tertiary ether	Extend gasoline supply, increase apparent octane quality with some loss in mileage
Antiknock compounds	Lead alkykl, organo-manganese compounds	Increase octane quality

CI Engine Fuels

- ❖ Ignition delay (ID) is the prime factor for auto-ignition/knock.

- ❖ ID is the time between start of injection and initiation of combustion.

  - ❑ Long ID ⇒ Rapid pressure rise ⇒ Knock
  - ❑ Short ID ⇒ incomplete mixing/smoke production

❖ Ignition quality : Cetane Number

Rating of CI Engine Fuel

- **Reference Fuels**
  - Cetane ($C_{16}H_{34}$) ⇒ 100 Cetane No.
  - α-methyl naphthalene ($C_{11}H_{10}$) ⇒ Zero Cetane No.

- **Fuel with Cetane Number of 60 indicates**
  - 60 % $C_{16}H_{34}$
  - 40 % $C_{11}H_{10}$

Definition: It indicates the % by volume of normal cetane in a mixture of Cetane ($C_{16}H_{34}$) and α-methyl naphthalene ($C_{11}H_{10}$) which exhibit the same ignition characteristics (ID) as the test fuel when combustion is carried out under specified operating conditions.

CI Engine Fuels

- Cetane number is a measure of its ability to auto-ignite quickly when the fuel is injected into the combustion chamber.

- Higher the CN, lesser is the tendency to knock. *Further, too high a Cetane number may induce pre-ignition.*

- Diesel usually has a cetane number between 40-60, whereas gasoline has a cetane number of 10-20. This is why it is not suitable as diesel fuel due to its poor auto-ignition quality. *A good diesel engine fuel is a bad gasoline engine fuel.*

Qualities of CI Engine Fuel

- It should have good antiknock quality. Must have short ignition delay.
- Must be sufficiently volatile in the operating range to ensure proper mixing and complete combustion.
- Should not promote smoke in the exhaust.
- Should not cause corrosion/wear in the engine components.
- Easy handling/availability.

TABLE 2.13
ASTM D975 diesel fuel specifications [by permission of ASTM © 1996]

	No. 1D	No. 2D	No. 4D
Flash point (°C, minimum)	38	52	55
Cloud point (°C)	Local requirement	Local requirement	Local requirement
Water and sediment (vol %, max)	0.05	0.05	0.05
Carbon residue 10% Btm (%, max)	0.15	0.35	—
Ash, wt (%, max)	0.01	0.01	0.10
Distillation 90% point (°C)	288 max	282–338	—
Viscosity at 40°C (cSt)	1.3–2.4	1.9–4.1	5.5–24
Sulfur (wt %, max)	0.05	0.05	2.0
Copper strip corrosion, max	No. 3	No. 3	—
Cetane no. (minimum)	40	40	30

Fuel no. 1D is used for cold weather applications, and no. 2D is the most common fuel for Diesel vehicles. Number 4D is is used for medium- to low-speed engines used for stationary applications.

Diesel Fuel

- In terms of combustion considerations, the major factors are viscosity and cetane number. Although the primary effect of low cetane number is to cause cold starting problems, reduction of cetane number can also increase engine roughness, peak pressure, and NO emissions. Typically, highly turbocharged engines are more tolerant to low cetane number during steady-state operation.

- Diesel fuels can also be improved by addition of fuel-additives.

Automotive diesel fuel additives

Additive	Type	Function
Detergents	Polyglycols, basic nitrogen-containing surfactants	Prevent injector deposits, increase injector life
Dispersants	Nitrogen-containing surfactants	Peptize soot and products of fuel oxidant; increase filter life
Metal deactivators	Chelating agents	Inhibit gum formation
Rust and corrosion inhibitors	Amines, amine carboxylates, and carboxylic acids	Prevent rust and corrosion in pipelines and fuel systems
Cetane improvers	Nitrate esters	Increase cetane number
Flow improvers	Polymers, wax crystal	Reduce pour point modifiers
Antismoke additions or smoke suppressants	Organic barium compounds	Reduce exhaust smoke
Oxidation inhibitors	Low–molecular weight amines	Minimize deposits in filters and injectors
Biocides	Boron compounds	Inhibit growth of bacteria and microorganisms

Summary

TABLE A-2 PROPERTIES OF FUELS

Fuel		Molecular Weight	Heating Value HHV (kJ/kg)	Heating Value LHV (kJ/kg)	Stoichiometric $(AF)_s$	Stoichiometric $(FA)_s$	Octane Number MON	Octane Number RON	Heat of Vaporization (kJ/kg)	Cetane Number
gasoline	C_8H_{15}	111	47300	43000	14.6	0.068	80–91	92–99	307	
light diesel	$C_{12.3}H_{22.2}$	170	44800	42500	14.5	0.069			270	40–55
heavy diesel	$C_{14.6}H_{24.8}$	200	43800	41400	14.5	0.069			230	35–50
isooctane	C_8H_{18}	114	47810	44300	15.1	0.066	100	100	290	
methanol	CH_3OH	32	22540	20050	6.5	0.155	92	106	1147	
ethanol	C_2H_5OH	46	29710	26950	9.0	0.111	89	107	873	
methane	CH_4	16	55260	49770	17.2	0.058	120	120	509	
propane	C_3H_8	44	50180	46190	15.7	0.064	97	112	426	
nitromethane	CH_3NO_2	61	12000	10920	1.7	0.588			623	
heptane	C_7H_{16}	100	48070	44560	15.2	0.066	0	0	316	
cetane	$C_{16}H_{34}$	226	47280	43980	15.0	0.066			292	100
heptamethylnonane	$C_{12}H_{34}$	178			15.9	0.063				15
α-methylnaphthalene	$C_{11}H_{10}$	142			13.1	0.076				0
carbon monoxide	CO	28	10100	10100	2.5	0.405				
coal (carbon)	C	12	33800	33800	11.5	0.087				
butene-1	C_4H_8	56	48210	45040	14.8	0.068	80	99	390	
triptane	C_7H_{16}	100	47950	44440	15.2	0.066	101	112	288	
isodecane	$C_{10}H_{22}$	142	47590	44220	15.1	0.066	92	113		
toluene	C_7H_8	92	42500	40600	13.5	0.074	109	120	412	
hydrogen	H_2	2	141800	120000	34.5	0.029		90		

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