SI Engine Combustion II

Spark discharge characteristics

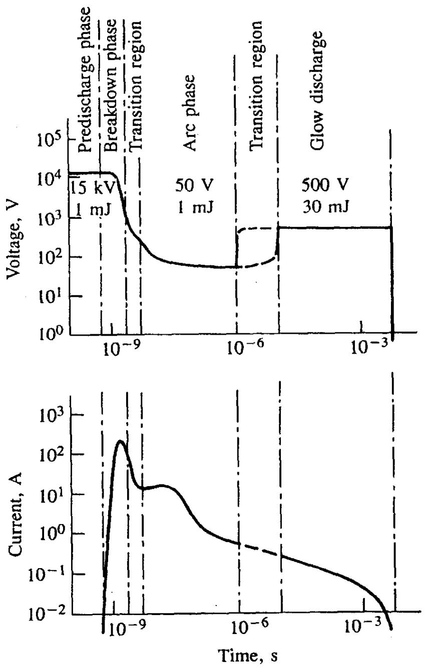
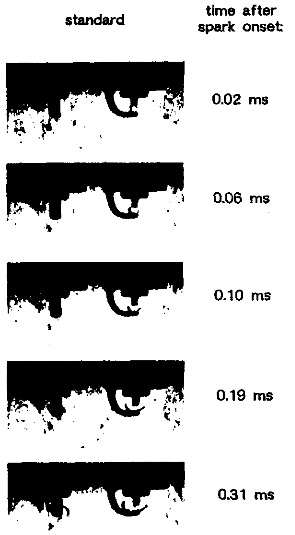
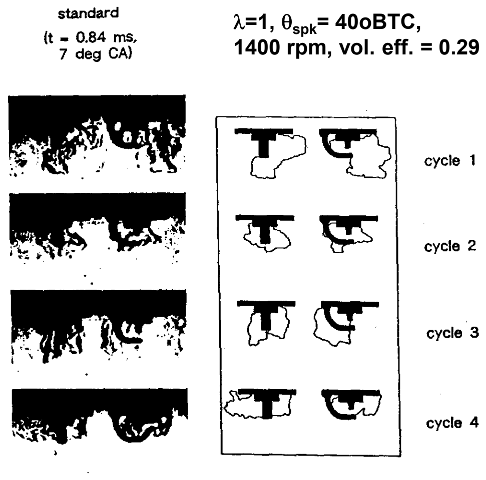


Fig.9-39
Schematic of voltage and current variation with time for conventional coil spark-ignition system.

Flame Kernel Development (SAE Paper 880518)

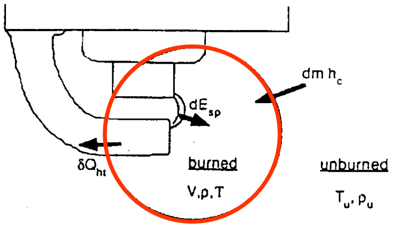


Single cycle flame sequence

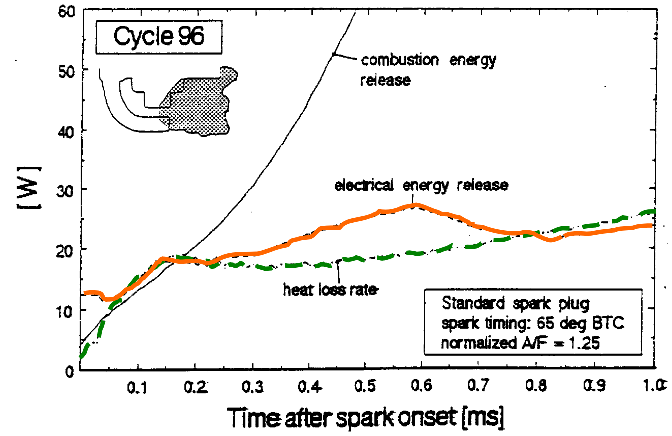


λ=1, θ_{spk}= 40oBTC, 1400 rpm, vol. eff. = 0.29

Flame from 4 consecutive cycles at fixed time after spark



Energy associated with Spark Discharge, Combustion and Heat Loss



SAE Paper 880518

Ignition and Flame Development Process

1. Spark discharge creates a high temperature plasma kernel which expands rapidly (1mm, 100 μs).

2. The hot reactive gas at the outer edge of this kernel causes the adjacent fuel-air mixture to ignite, creating an outward propagating flame which is almost spherical.

3. As the flame grows larger, the flame surface is distorted by the turbulence of the fluid motion. A wrinkled laminar flame results.

4. Because of the significant surface area enhancement by the wrinkling, the locally laminar “turbulent” flame burns rapidly.

Schematic of entrainment-and-burn model

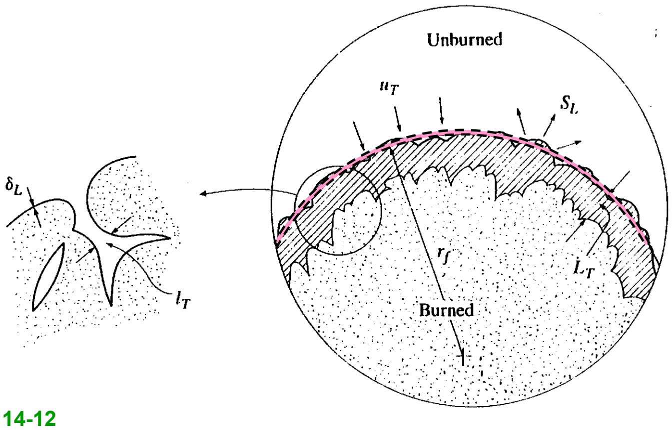


Fig. 14-12

SI engine flame propagation
Entrainment-and-burn model

Rate of entrainment:

$$\frac{dm_e}{dt} = \rho_u A_f S_L \; + \; \rho_u A_f u_T \left(1 - e^{-t/\tau_b}\right)$$

Laminar diffusion through flame front

Turbulent entrainment

Rate at which mixture burns:

$$\frac{dm_b}{dt} = \rho_u A_f S_L + \frac{m_e - m_b}{\tau_b} \; ; \qquad \tau_b = \frac{\ell_T}{S_L}$$

Laminar frontal burning

Conversion of entrained mass into burned mass

Critical parameters: u_T and ℓ_T

SI Engine design and operating factors affecting burn rate

1. Flame geometry:

   The frontal surface area of the flame directly affects the burn rate. This flame area depends on flame size, combustion chamber shape, spark plug location and piston position.

2. In-cylinder turbulence during combustion:

   The turbulence intensity and length scale control the wrinkling and stretching of the flame front, and affect the effective burning area. These parameters are determined largely by the intake generated flow field and the way that flow changes during compression.

3. Mixture composition and state:

   The local consumption of the fuel-air mixture at the flame front depends on the laminar flame speed S_L. The value of S_L depends on the fuel equivalence ratio, fraction of burned gases in the mixture (residual plus EGR), and the mixture temperature and pressure.

Cycle-to-cycle variations

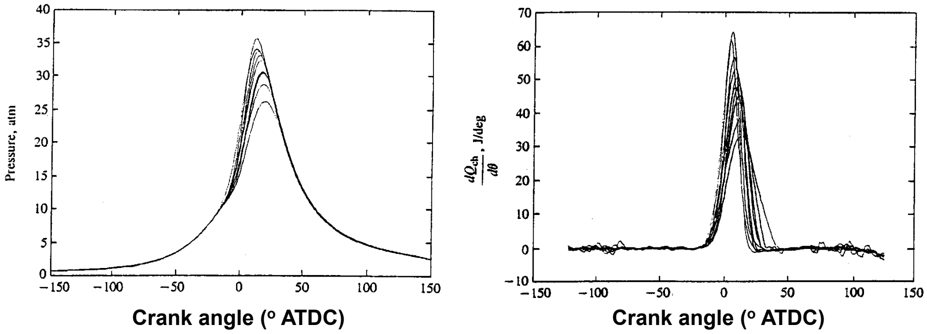
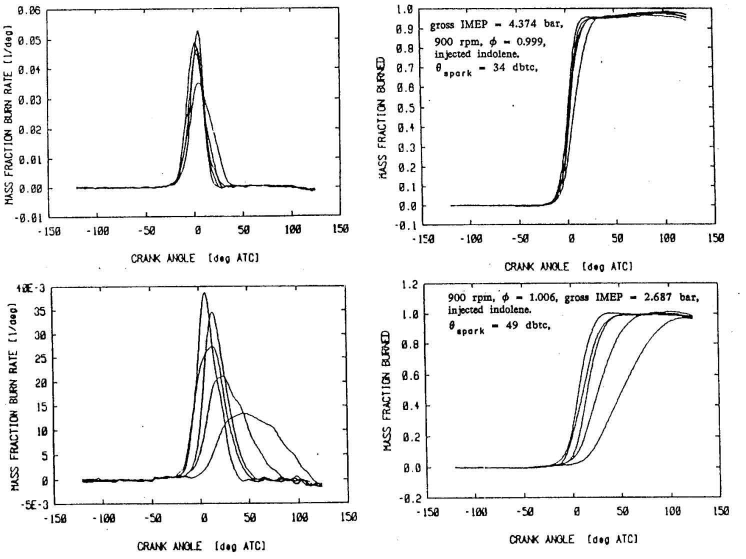


Fig. 9-31

Measured cylinder pressure and calculated gross heat-release rate for ten cycles in a single-cylinder SI engine operating at 1500 rpm, Φ = 1.0, MAP = 0.7 bar, MBT timing 25°BTC

Cycle-to-cycle change in combustion phasing



SI ENGINE CYCLE-TO-CYCLE VARIATIONS

Phases of combustion

1. Early flame development
2. Flame propagation
3. Late stage of burning

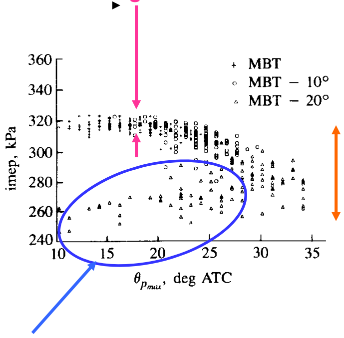
Factors affecting SI engine cycle-to-cycle variations:

(a) Spark energy deposition in gas (1)
(b) Flame kernel motion (1)
(c) Heat losses from kernel to spark plug (1)
(d) Local turbulence characteristics near plug (1)
(e) Local mixture composition near plug (1)
(f) Overall charge components - air, fuel, residual (2, 3)
(g) Average turbulence in the combustion chamber (2, 3)
(h) Large scale features of the in-cylinder flow (3)
(i) Flame geometry interaction with the combustion chamber (3)

Cycle distributions

Fig,. 9-33 (b)

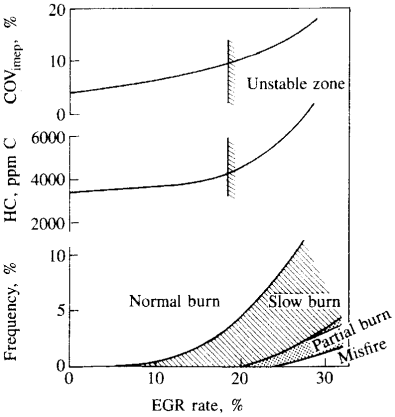
Charge variations



Charge and combustion duration variations

Very Slow-burn cycles

Fig,. 9-36 (b)



Partial burn – substantial combustion inefficiency (10-70%)
Misfire – significant combustion inefficiency (>70%)
(No definitive value for threshold)

Knock

Processes

- Auto-ignition
- Rapid heat release
- Pressure oscillation

Consequences

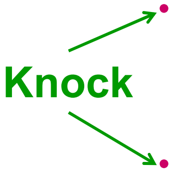
- Audible noise
- Damage to combustion chamber in severe knock

How to “burn” things?

Reactants → Products

Premixed

- Premixed flame
  - Examples: gas grill, SI engine combustion
- Homogeneous reaction
  - Fast/slow reactions compared with other time scale of interest
  - Not limited by transport process
- Detonation
  - Pressure wave driven reaction



Non-premixed

- Diffusion flame
  - Examples: candle, diesel engine combustion

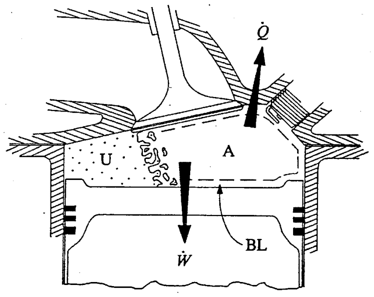
SI engine Combustion

Normal combustion

- Spark initiated premixed flame

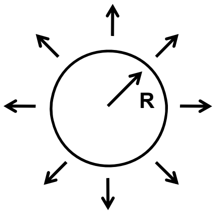
Abnormal combustion

- Pre-ignition (“diesel”)
  - Ignition by hot surfaces or other means
- End gas knock (“spark knock”)
  - Compression ignition of the not-yet-burned mixture (end gas)
  - Affected by spark timing



Heat release rate and pressure wave

- When acoustic expansion is not fast enough to alleviate local pressure buildup due to heat release, pressure wave develops



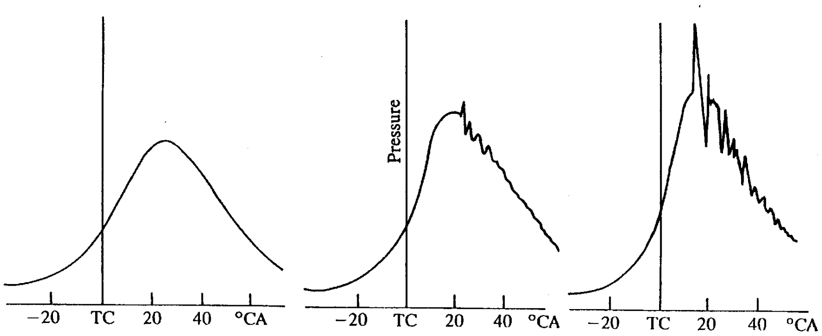
$\dot{q}$ = Heat release per unit volume over sphere of radius R

a = Sound speed

Critirion for setting up pressure wave:

$$\dot{q} \ge \frac{3\gamma}{\gamma - 1}\frac{ap}{R}$$

Pressure oscillations observed in engine knock



(*a*) Normal combustion, spark 28°BTC

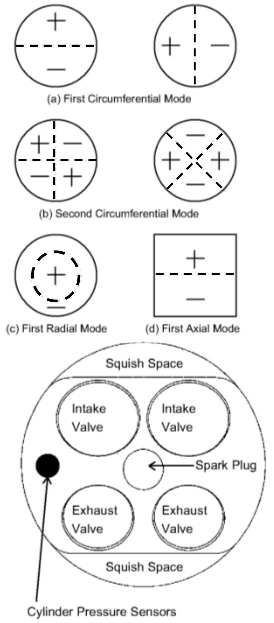
(*b*) Slight knock, spark 28°BTC

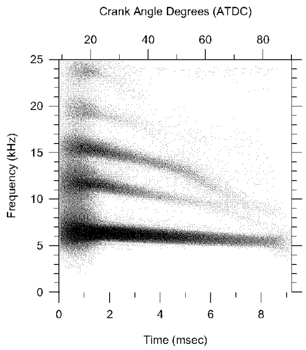
(*c*) Intense knock, spark 32°BTC

Single cylinder engine, 381 cc displacement; 4000 rpm, WOT

Fig. 9-59

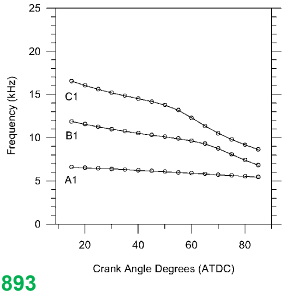
Acoustic modes





Spectrogram of 4 valve engine knock pressure data

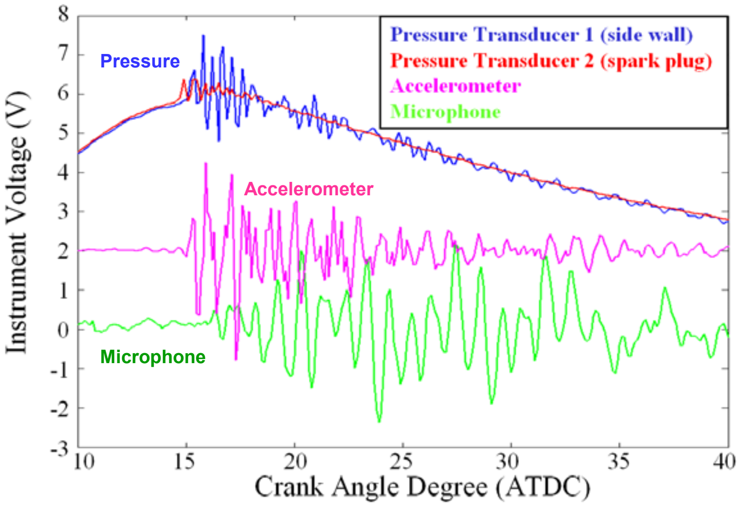
(2L I-4 engine; CR=9.6)



Calculated acoustic frequency of modes by FEM

SAE Paper 980893

Steps to Audible Knock

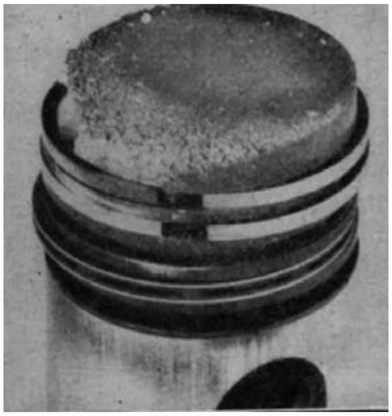


Auto-ignition
↓
Pressure oscillation
↓
Block vibration
↓
Audible noise

Heavy Knock/ detonation

- Rapid combustion of stoichiometric mixture at compressed condition
  - Approximately constant volume
  - Local P ~ 100 to 150 bar
  - Local T > 2800ºK
- High pressure and high temperature lead to structural damage of combustion chamber

Knock damaged pistons



From Lichty, *Internal Combustion Engines*

From Lawrence Livermore website

Knock Fundamentals

Knock originates in the extremely rapid release of much of the fuel chemical energy contained in the end-gas of the propagating turbulent flame, resulting in high local pressures. The non-uniform pressure distribution causes strong pressure waves or shock waves to propagate across and excites the acoustic modes of the combustion chamber.

When the fuel-air mixture in the end-gas region is compressed to sufficiently high pressures and temperatures, the fuel oxidation process — starting with the pre-flame chemistry and ending with rapid heat release — can occur spontaneously in parts or all of the end-gas region.

Most evidence indicates that knock originates with the auto-ignition of one or more local regions within the end-gas. Additional regions then ignite until the end-gas is essentially fully reacted. The sequence of processes occur extremely rapidly.

Knock chemical mechanism

CHAIN BRANCHING EXPLOSION

Chemical reactions lead to increasing number of radicals, which leads to rapidly increasing reaction rates

Chain Initiation

$$RH + O_2 \Rightarrow \dot{R} + H\dot{O}_2$$

Chain Propagation

$$\dot{R} + O_2 \Rightarrow R\dot{O}_2, \text{etc.}$$

Formation of Branching Agents

$$R\dot{O}_2 + RH \Rightarrow ROOH + \dot{R}$$

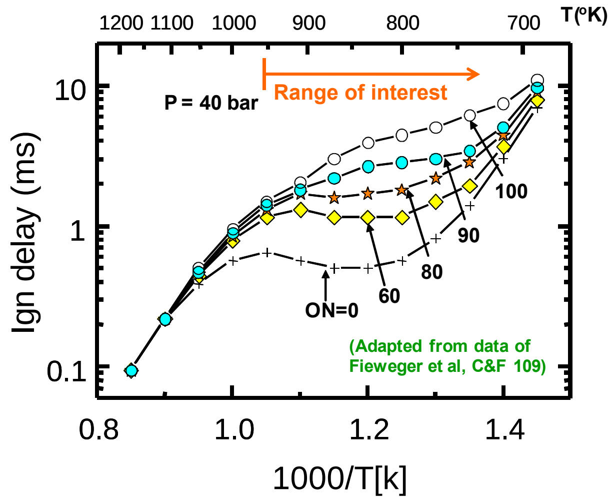
$$R\dot{O}_2 \Rightarrow R'CHO + R''\dot{O}$$

Degenerate Branching

$$ROOH \Rightarrow R\dot{O} + \dot{O}H$$

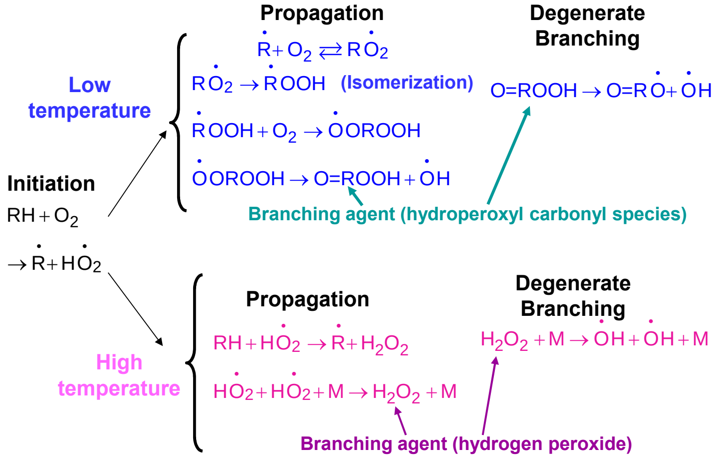
$$R'CHO + O_2 \Rightarrow R'\dot{C}O + H\dot{O}_2$$

Ignition delay for primary reference fuels



(Adapted from data of Fieweger et al, C&F 109)

Ignition delay kinetics



Initiation

$RH+O_2 \rightarrow \dot{R}+H\dot{O}_2$

Low temperature

Propagation

$\dot{R}+O_2 \rightleftarrows R\dot{O}_2$

$R\dot{O}_2 \rightarrow \dot{R}OOH$ **(Isomerization)**

$\dot{R}OOH+O_2 \rightarrow \dot{O}OROOH$

$\dot{O}OROOH \rightarrow O{=}ROOH+\dot{O}H$

Degenerate Branching

$O{=}ROOH \rightarrow O{=}R\dot{O}+\dot{O}H$

Branching agent (hydroperoxyl carbonyl species)

High temperature

Propagation

$RH+H\dot{O}_2 \rightarrow \dot{R}+H_2O_2$

$H\dot{O}_2+H\dot{O}_2+M \rightarrow H_2O_2+M$

Degenerate Branching

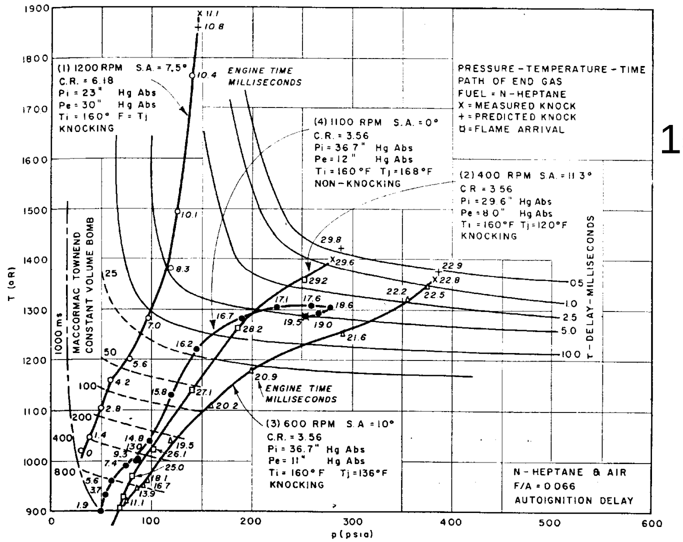
$H_2O_2+M \rightarrow \dot{O}H+\dot{O}H+M$

Branching agent (hydrogen peroxide)

NTC regime

Temperature high enough to shift formation of RO_2 to H_2O_2, but not high enough for H_2O_2 decomposition

Livengood and Wu integral



5th Combustion Symposium, 1954

$$1=\int^{t_{ign}}\frac{dt}{\tau(p(t),T(t))}$$

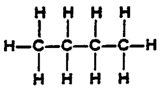
FUEL FACTORS

- The auto-ignition process depends on the fuel chemistry.
- Practical fuels are blends of a large number of individual hydrocarbon compounds, each of which has its own chemical behavior.
- A practical measure of a fuel’s resistance to knock is the octane number. High octane number fuels are more resistant to knock.

Types of hydrocarbons

(See text section 3.3)

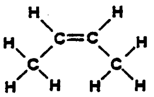
PARAFFINS



Butane

The carbon atoms in paraffins are held together chemically by single bonds. Paraffins have the general formula C_nH_{2n-2} with "n" indicating the number of carbon atoms.

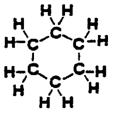
OLEFINS



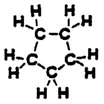
cis-2-Butene

Olefins are similar to paraffins, but they have two fewer hydrogen atoms and contain one double bond between two of the carbon atoms. Olefins have the general formula C_nH_{2n}. They rarely occur naturally in crude oil, but are formed in the refining process. Olefins may also be cyclic, resembling a naphthene with a double bond.

NAPHTHENES



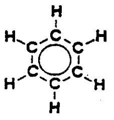
Cyclohexane



Cyclopentane

Naphthenes are also called "cycloparaffins," because the carbon atoms are arranged in a ring structure — usually of five or six carbon atoms. If all the carbon atoms are held together by single bonds, naphthenes have the same general formula as olefins, C_nH_{2n}.

AROMATICS

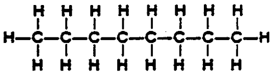


Benzene

Aromatics are odorous, ring-type hydrocarbons. The carbon atoms are joined by "aromatic" bonds, which are actually hybrids of single and double bonds.

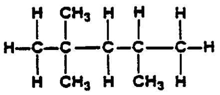
ISOMERS

There is one more thing you should know about paraffins and olefins. Paraffins with four or more carbon atoms can exist in more than one form. Butane, with four carbon atoms, is the simplest member of the paraffins in which it is possible to form two or more distinctly different chemical structures using the same number of hydrogen and carbon atoms. These variations are called isomers. For example, normal octane is a straight-chain hydrocarbon. It has 8 carbon and 18 hydrogen atoms and it looks like this:



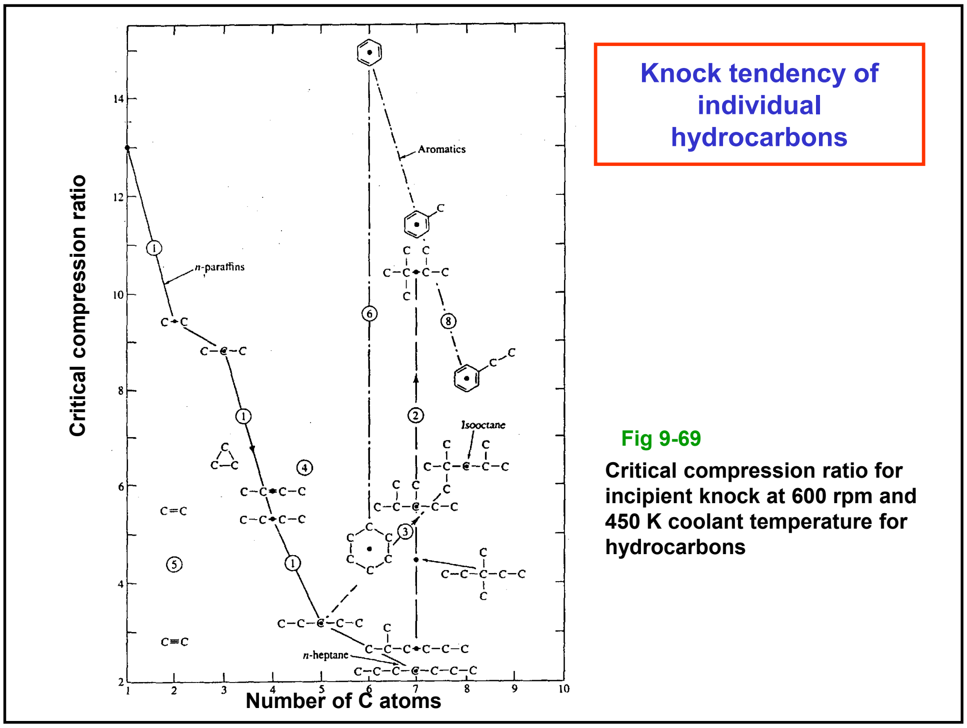
n-Octane

Isooctane is one of the isomers of octane. It also has eight carbon and eighteen hydrogen atoms, but they form a branched chain, as in this example:



2,2,4-Trimethylpentane

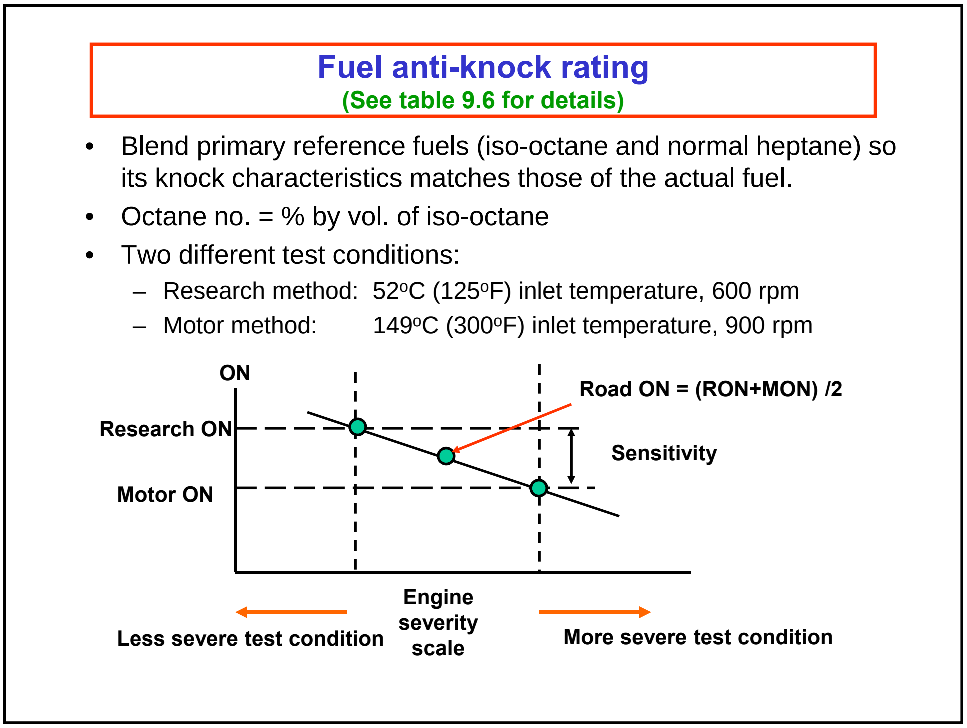
Different isomers do not have the same properties. Isooctane is less likely to knock than normal octane — it has an RON of 100, compared to only 25 for its straight-chain cousin. Not surprisingly, it has become a standard for rating the performance of a gasoline.



Knock tendency of individual hydrocarbons

Fig 9-69

Critical compression ratio for incipient knock at 600 rpm and 450 K coolant temperature for hydrocarbons



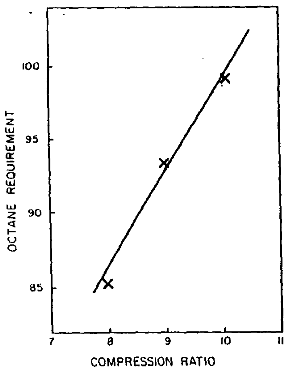
Fuel anti-knock rating

(See table 9.6 for details)

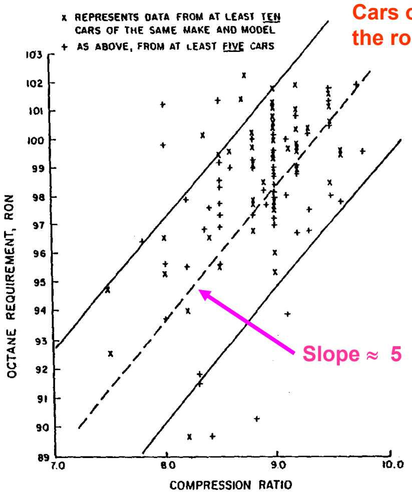
- Blend primary reference fuels (iso-octane and normal heptane) so its knock characteristics matches those of the actual fuel.
- Octane no. = % by vol. of iso-octane
- Two different test conditions:
  - Research method: 52°C (125°F) inlet temperature, 600 rpm
  - Motor method: 149°C (300°F) inlet temperature, 900 rpm

Octane requirement

Engine on test stand



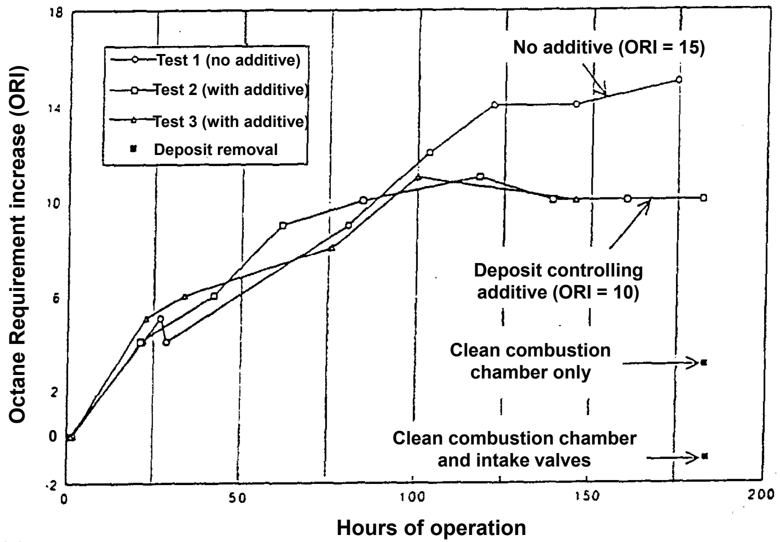
Cars on the road



Slope ≈ 5

From Balckmore and Thomas, *Fuel Economy of the Gasoline Engine*, Wiley 1977.

Octane Requirement Increase



No additive (ORI = 15)

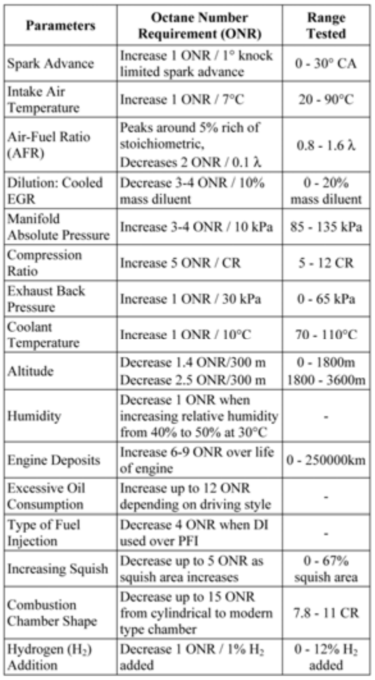
Deposit controlling additive (ORI = 10)

Clean combustion chamber only

Clean combustion chamber and intake valves

ACS Vol. 36, #1, 1991

ONR with change of engine parameters



Parameters	Octane Number Requirement (ONR)	Range Tested
Spark Advance	Increase 1 ONR / 1° knock limited spark advance	0 - 30° CA
Intake Air Temperature	Increase 1 ONR / 7°C	20 - 90°C
Air-Fuel Ratio (AFR)	Peaks around 5% rich of stoichiometric, Decreases 2 ONR / 0.1 λ	0.8 - 1.6 λ
Dilution: Cooled EGR	Decrease 3-4 ONR / 10% mass diluent	0 - 20% mass diluent
Manifold Absolute Pressure	Increase 3-4 ONR / 10 kPa	85 - 135 kPa
Compression Ratio	Increase 5 ONR / CR	5 - 12 CR
Exhaust Back Pressure	Increase 1 ONR / 30 kPa	0 - 65 kPa
Coolant Temperature	Increase 1 ONR / 10°C	70 - 110°C
Altitude	Decrease 1.4 ONR/300 m Decrease 2.5 ONR/300 m	0 - 1800m 1800 - 3600m
Humidity	Decrease 1 ONR when increasing relative humidity from 40% to 50% at 30°C	-
Engine Deposits	Increase 6-9 ONR over life of engine	0 - 250000km
Excessive Oil Consumption	Increase up to 12 ONR depending on driving style	-
Type of Fuel Injection	Decrease 4 ONR when DI used over PFI	-
Increasing Squish	Decrease up to 5 ONR as squish area increases	0 - 67% squish area
Combustion Chamber Shape	Decrease up to 15 ONR from cylindrical to modern type chamber	7.8 - 11 CR
Hydrogen (H_2) Addition	Decrease 1 ONR / 1% H_2 added	0 - 12% H_2 added

From SAE Paper 2012-01-1143

Knock control strategies

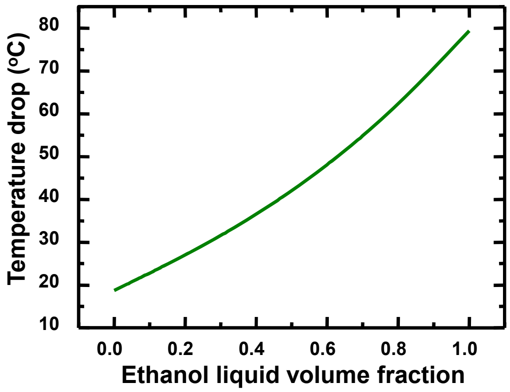
1. Provide adequate cooling to the engine
2. Use intercooler on turbo-charged engines
3. Use high octane gasoline
4. Anti-knock gasoline additives
5. Fuel enrichment under severe condition
6. Use knock sensor to control spark retard so as to operate close to engine knock limit
7. Fast burn system
8. Gasoline direct injection

Anti-knock Agents

Alcohols	
Methanol	CH_3OH
Ethanol	C_2H_5OH
TBA (Tertiary Butyl Alcohol)	$(CH_3)_3COH$

Ethers	
MTBE (Methyl Tertiary Butyl Ether)	$(CH_3)_3COCH_3$
ETBE (Ethyl Tertiary Butyl Ether)	$(CH_3)_3COC_2H_5$
TAME (Tertiary Amyl Methyl Ether)	$(CH_3)_2(C_2H_5)COCH_3$

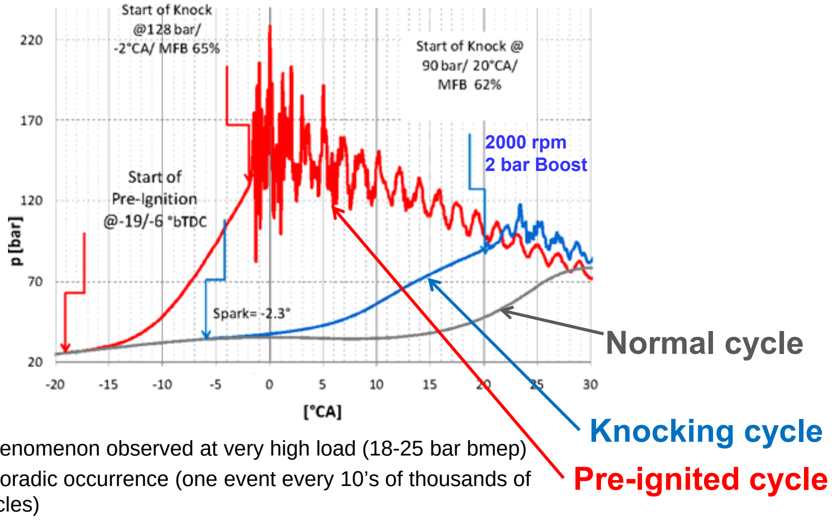
Adiabatic cooling of gasoline/ ethanol mixture



Preparing a stoichiometric mixture from air and liquid fuel

Note that Evaporation stops when temperature drops to dew point of the fuel in vapor phase

Sporadic Pre-ignition (super-knock)



- Phenomenon observed at very high load (18-25 bar bmep)
- Sporadic occurrence (one event every 10's of thousands of cycles)
- Each event may be one or more knocking cycles
- Mechanism not yet defined (oil, deposit, …?)

SI Engine Knock

1. Knock is most critical at WOT and at low speed because of its persistence and potential for damage. Part-throttle knock is a transient phenomenon and is a nuisance to the driver.
2. Whether or not knock occurs depends on engine/fuel/vehicle factors and ambient conditions (temperature, humidity). This makes it a complex phenomenon.
3. To avoid knock with gasoline, the engine compression ratio is limited to approximately 12.5 in PFI engines and 13.5 in DISI engines. Significant efficiency gains are possible if the compression ratio could be raised. (Approximately, increasing CR by 1 increases efficiency by one percentage point.)
4. Feedback control of spark timing using a knock sensor is increasingly used so that SI engine can operate close to its knock limit.