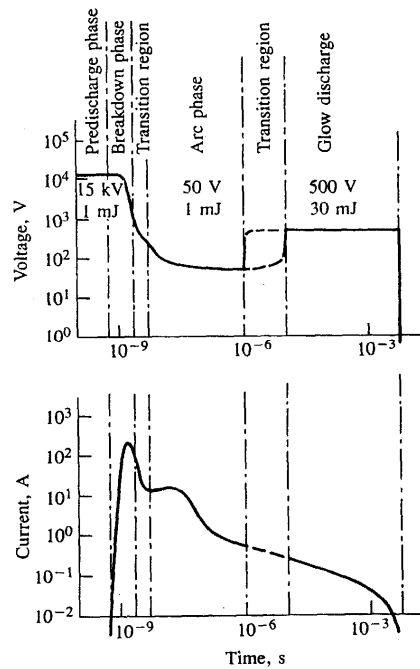


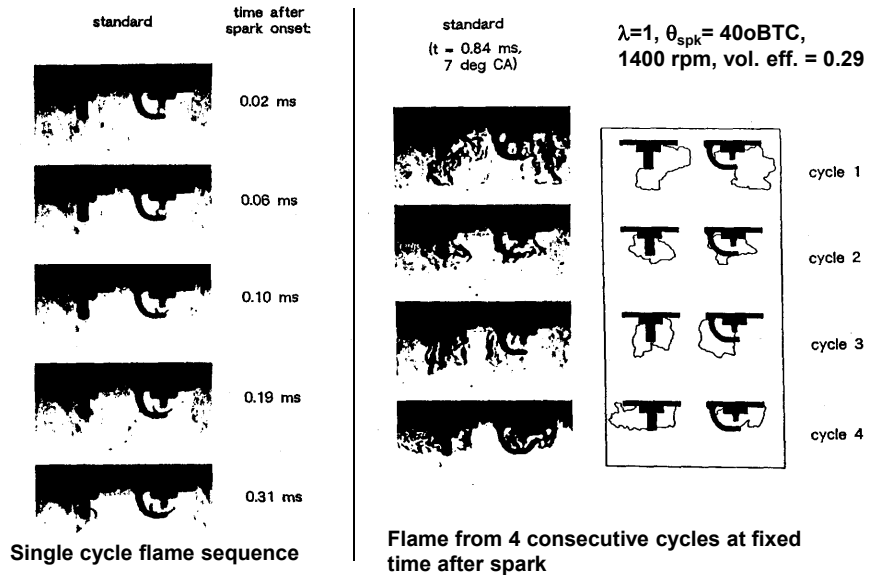
## SI Engine Combustion II



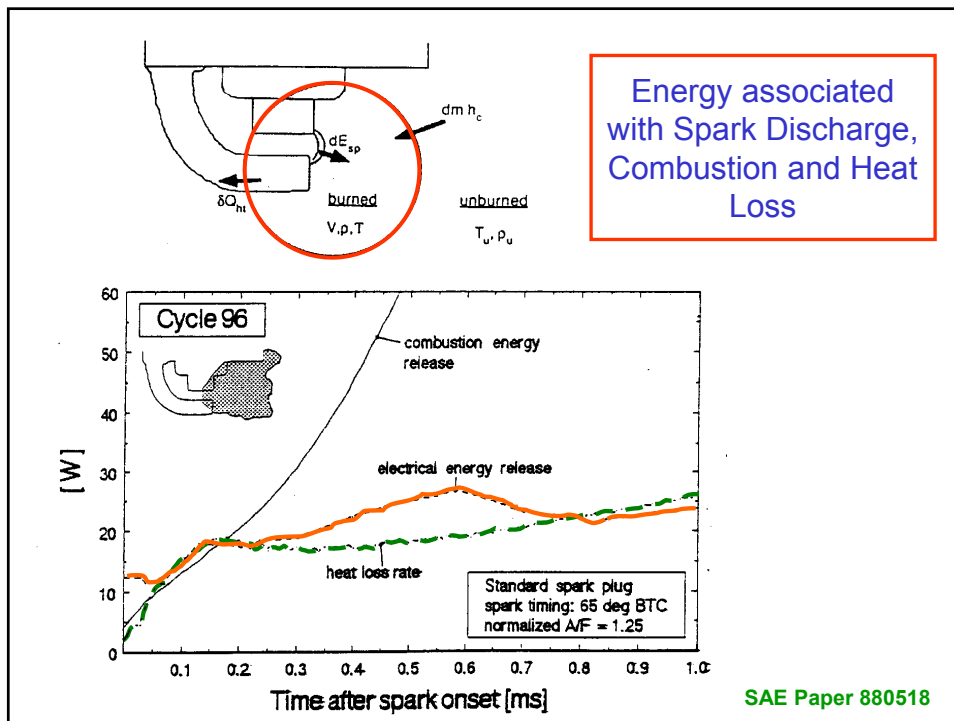
### Spark discharge characteristics

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

## Flame Kernel Development (SAE Paper 880518)



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## Ignition and Flame Development Process

1. Spark discharge creates a high temperature plasma kernel which expands rapidly (1mm, 100  $\mu$ s).
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

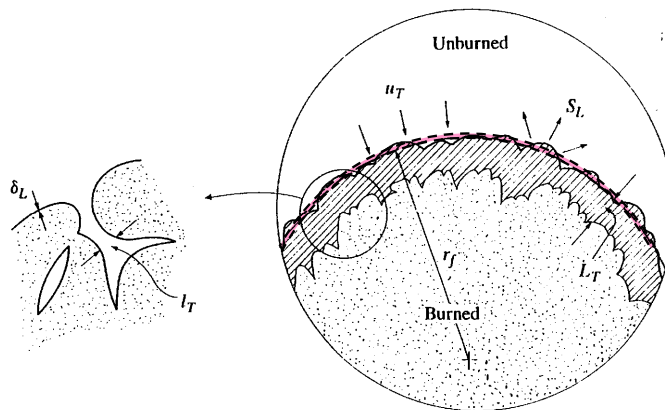


Fig. 14-12

## SI engine flame propagation Entrainment-and-burn model

Rate of entrainment:

$$\frac{d\dot{V}}{dt} = \rho_u U_s \dot{A} + \rho_u C_D v_s \dot{V} \frac{v_s}{U_s} = \rho_u U_s \dot{A} + \rho_u C_D v_s \dot{V} \frac{v_s}{U_s}$$

Laminar diffusion through flame front
Turbulent entrainment

Rate at which mixture burns:

$$\frac{d\dot{m}}{dt} = \rho_u U_s \dot{A} \frac{v_s}{U_s} + \frac{\dot{V}}{\tau_b} \quad \tau_b = \frac{l_f}{U_s}$$

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

**FÉ** Øæ ^Á^ { ^d^K

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.

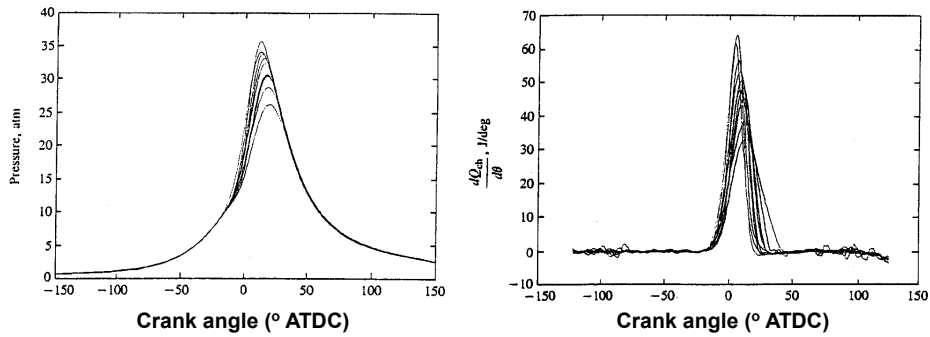
**GÈ** QÈ&|å à^!Á: |à^ |^} &^Á~ |å \*^& { à^ •å } K

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.

**HÈ** T æc !^& [ ] [ •å ] Áå àÁææK

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.

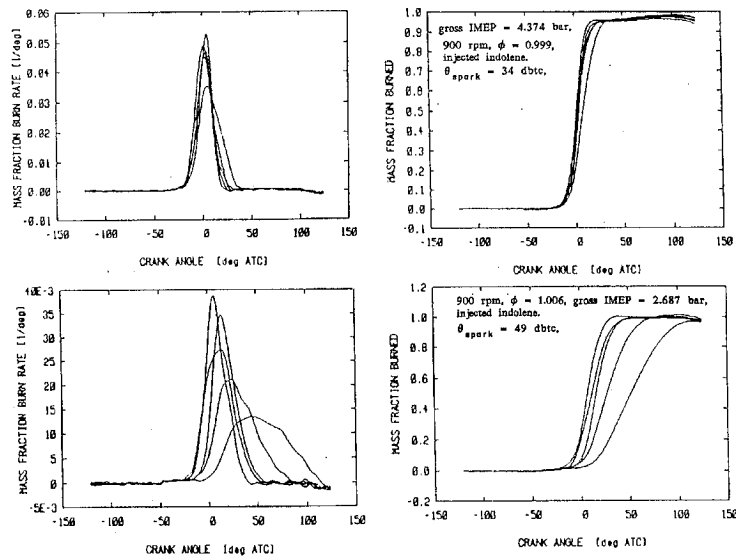
## Cycle-to-cycle variations



**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,  $\Phi = 1.0$ , MAP = 0.7 bar, MBT timing 25°BTC

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## 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)

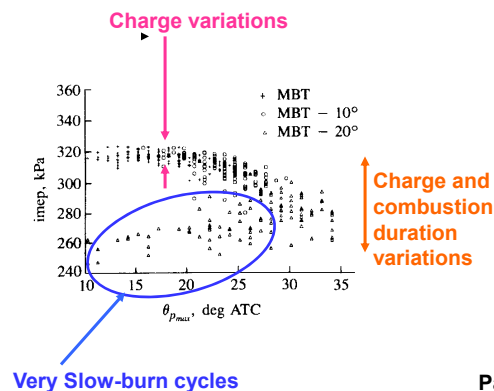
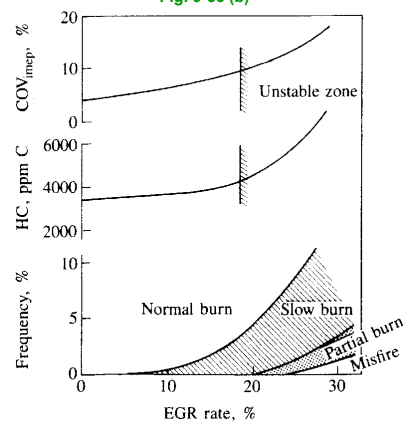


Fig. 9-36 (b)



**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

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## 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

Knock

### Non-premixed

- Diffusion flame
  - Examples: candle, diesel engine combustion

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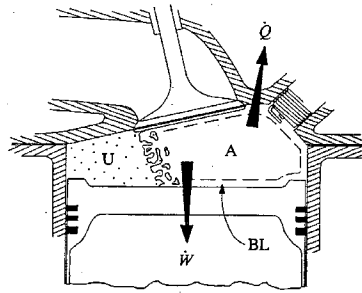
## SI engine Combustion

### 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

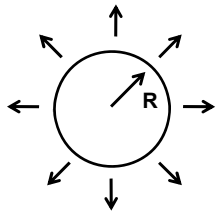


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## Heat release rate and pressure wave

- 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

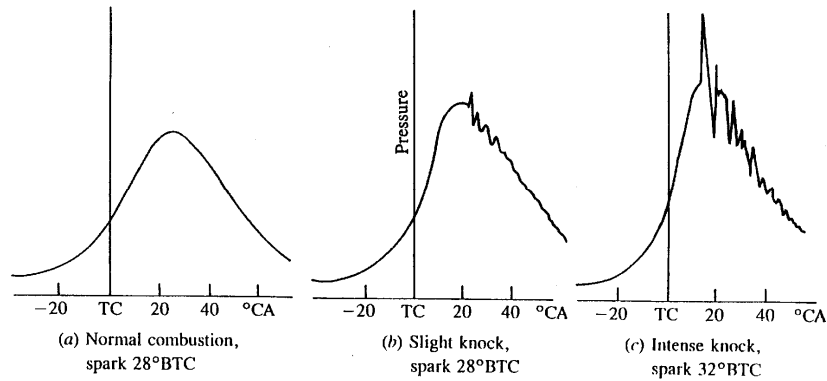
Critirion for setting up pressure wave:

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

16



## Pressure oscillations observed in engine knock



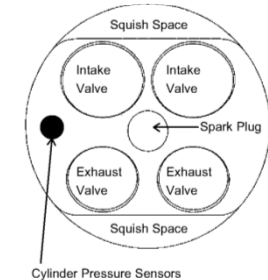
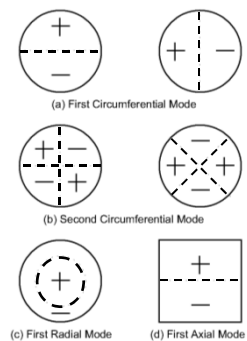
Single cylinder engine, 381 cc displacement; 4000 rpm, WOT

Fig. 9-59

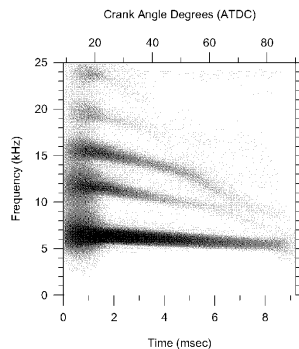
17

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## Acoustic modes

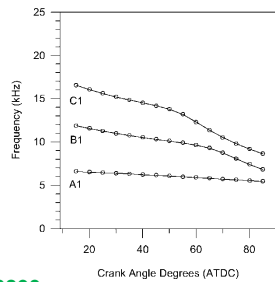


SAE Paper 980893



Spectrogram of 4 valve engine knock pressure data

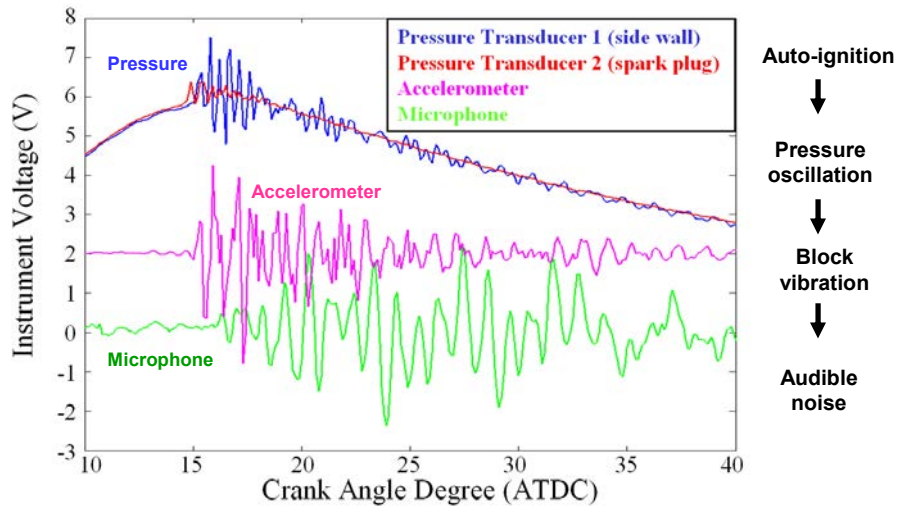
(2L I-4 engine; CR=9.6)



Calculated acoustic frequency of modes by FEM

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## Steps to Audible Knock



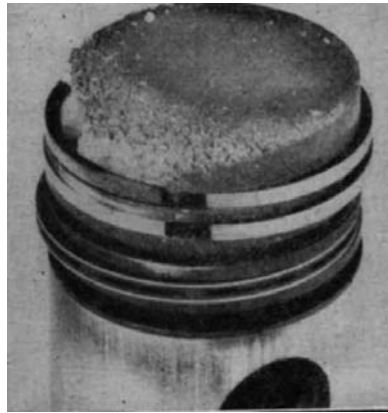
19

## Heavy Knock/ detonation

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

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## Knock damaged pistons



From Lichty, *Internal Combustion Engines*



From Lawrence Livermore website

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Image courtesy of Lawrence Livermore National Laboratory.

## 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.

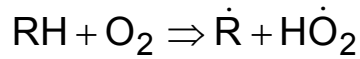
Most evidence indicates that knock originates with the auto-ignition of one or more local regions within the end-gas. Additional regions then ignite until the end-gas is essentially fully reacted. The sequence of processes occur extremely rapidly.

## Knock chemical mechanism

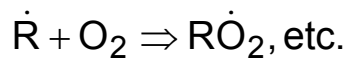
### CHAIN BRANCHING EXPLOSION

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

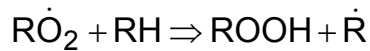
#### Chain Initiation



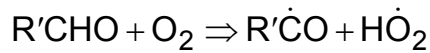
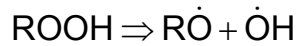
#### Chain Propagation



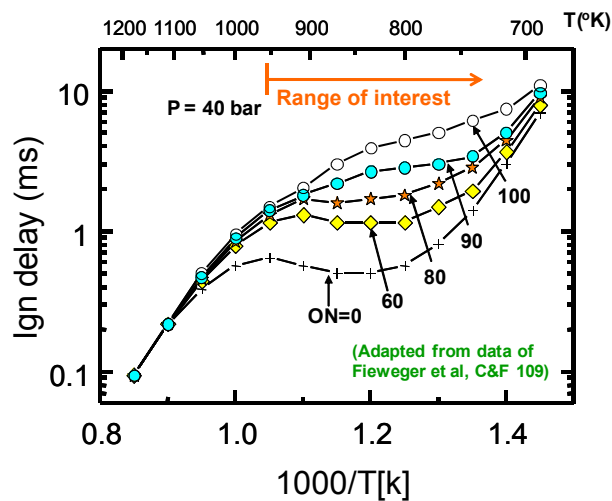
#### Formation of Branching Agents



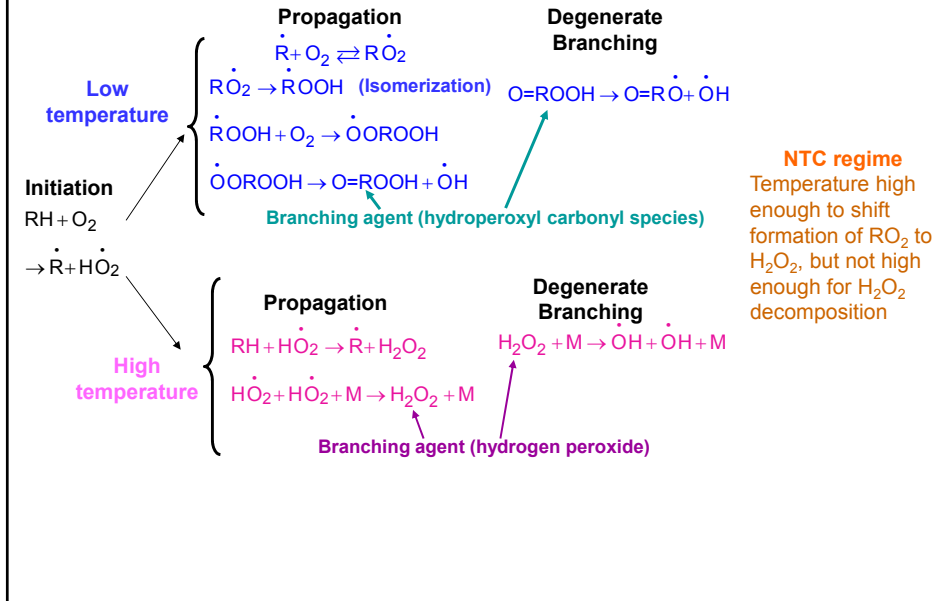
#### Degenerate Branching



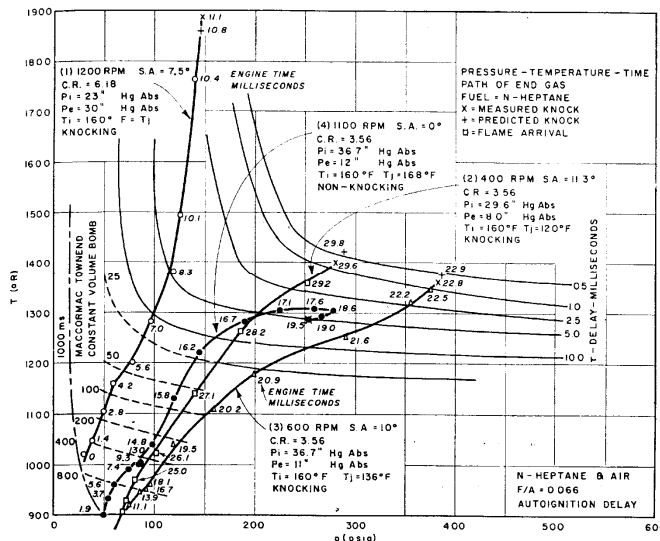
## Ignition delay for primary reference fuels



## Ignition delay kinetics



## Livengood and Wu integral



$$1 = \int_0^{t_{ign}} \frac{dt}{\tau(p(t), T(t))}$$

5th Combustion Symposium, 1954

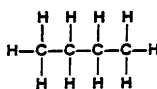
## FUEL FACTORS

- 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)

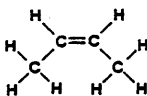
#### PARAFFINS



#### 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.

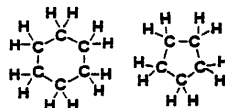
#### OLEFINS



#### 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.

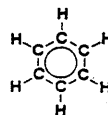
#### NAPHTHENES



#### 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

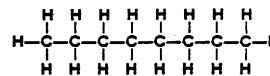


#### Benzene

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

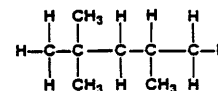
#### ISOMERS

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:



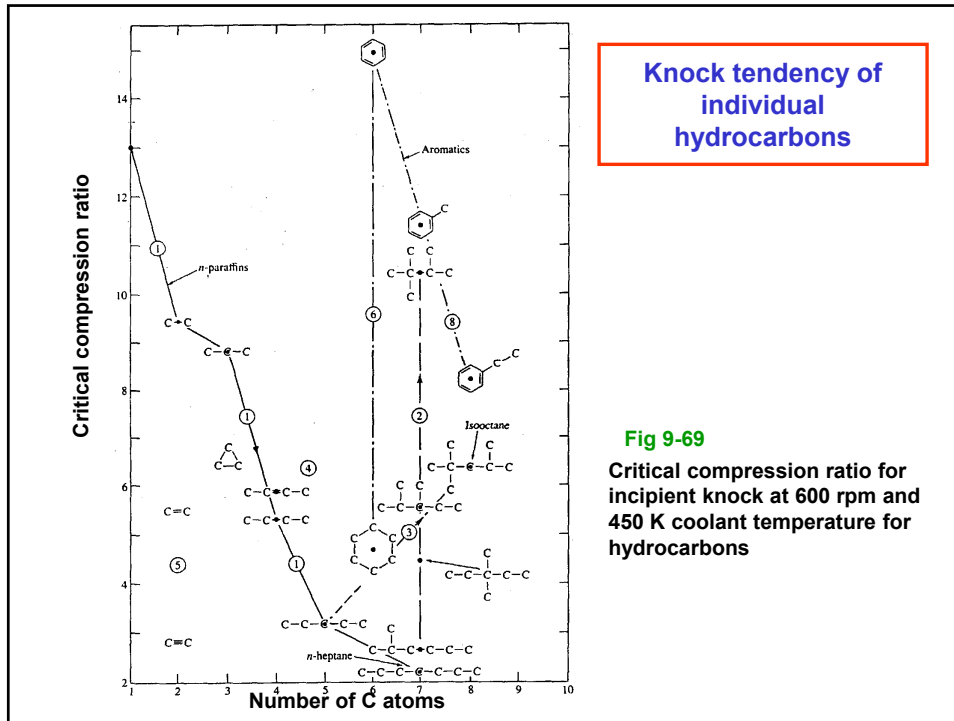
#### n-Octane

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:

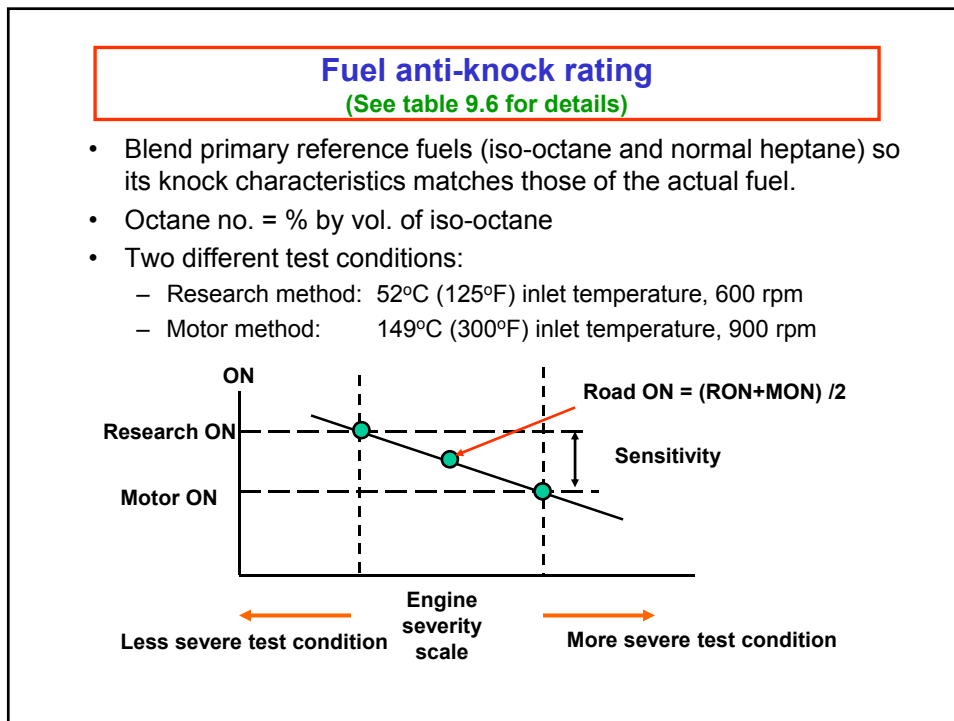


#### 2,2,4-Trimethylpentane

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.

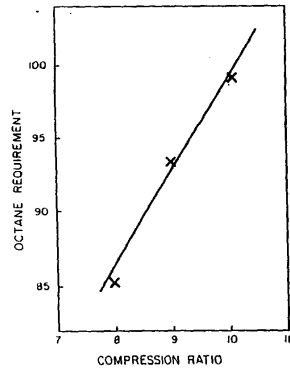


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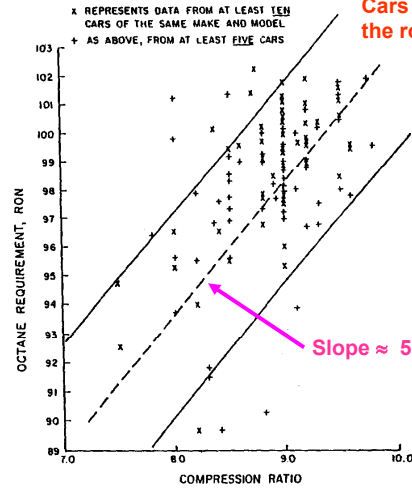


## Octane requirement

**Engine on test stand**



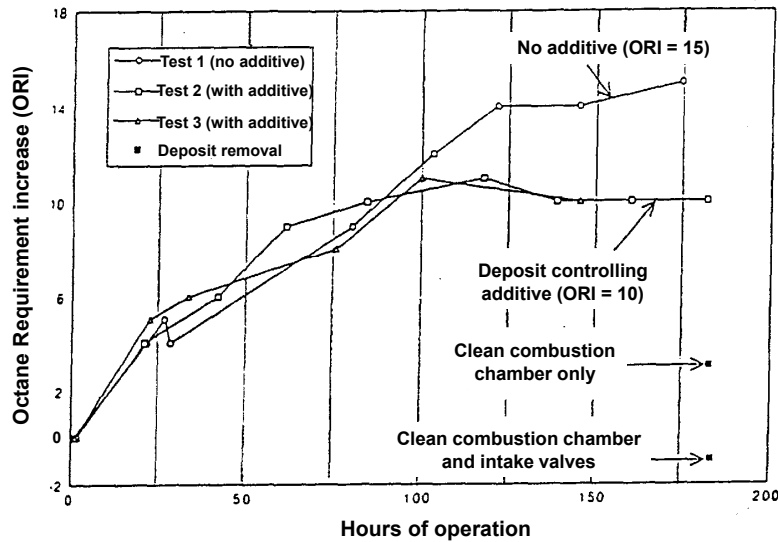
**Cars on the road**



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

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## Octane Requirement Increase



ACS Vol. 36, #1, 1991

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

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## 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

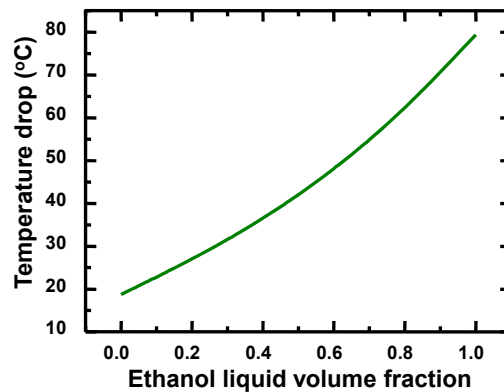
Methanol	$\text{CH}_3\text{OH}$
Ethanol	$\text{C}_2\text{H}_5\text{OH}$
TBA (Tertiary Butyl Alcohol)	$(\text{CH}_3)_3\text{COH}$

### Ethers

MTBE (Methyl Tertiary Butyl Ether)	$(\text{CH}_3)_3\text{COCH}_3$
ETBE (Ethyl Tertiary Butyl Ether)	$(\text{CH}_3)_3\text{COC}_2\text{H}_5$
TAME (Tertiary Amyl Methyl Ether)	$(\text{CH}_3)_2(\text{C}_2\text{H}_5)\text{COCH}_3$

## Adiabatic cooling of gasoline/ ethanol mixture

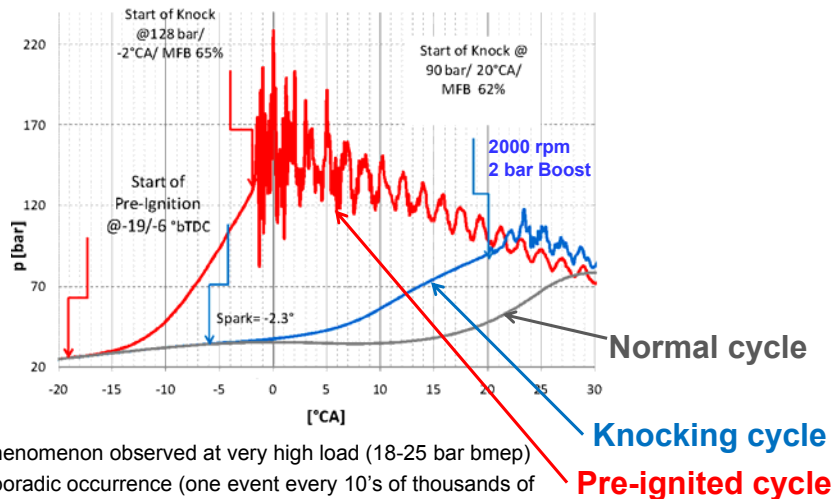
Preparing a stoichiometric mixture from air and liquid fuel



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

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## 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, ...?)

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## 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 used so that SI engine can operate close to its knock limit.

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2.61 Internal Combustion Engines  
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