A larger prechamber (5 to 12 percent) and larger orifice (orifice area/prechamber volume ratio of 0.04 to 0.2 cm^{-1}) gives a lower velocity jet which penetrates the main chamber charge more slowly, resulting in a slower burn.

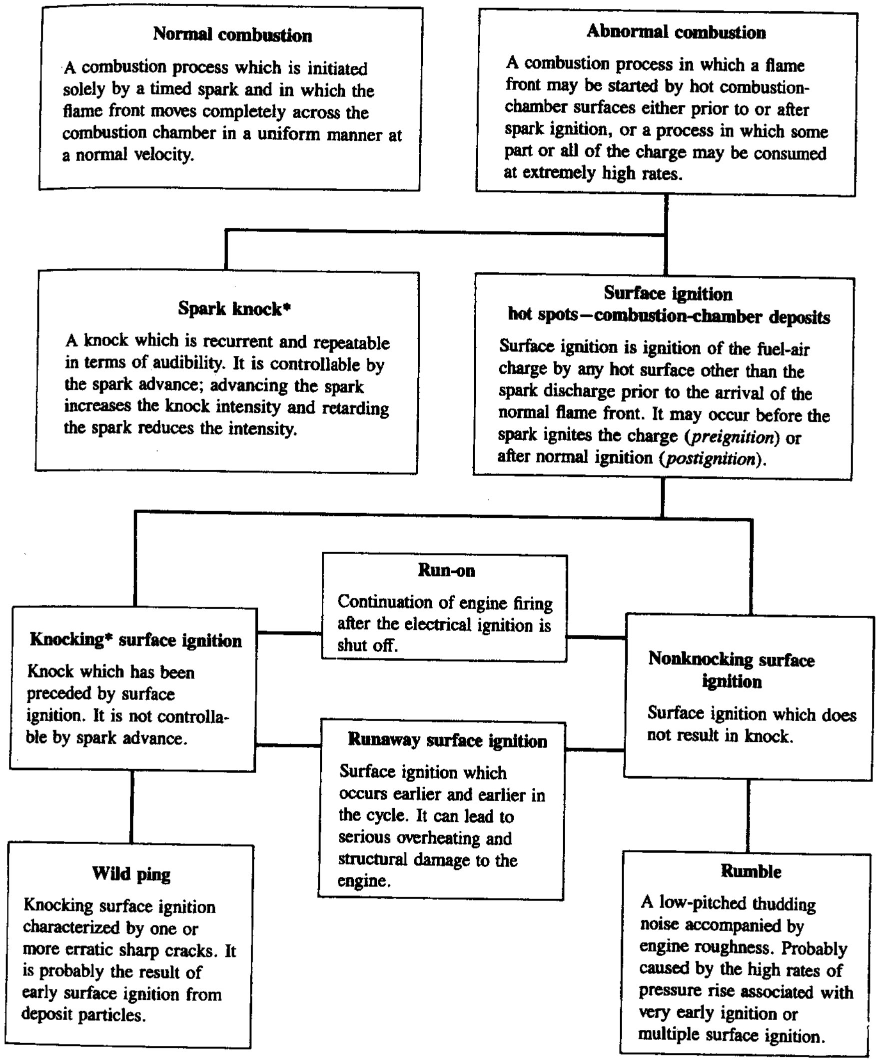
All these concepts extend the engine's lean stable operating limit, relative to equivalent conventional engines, by several air/fuel ratios. For example, the unscavenged cavity without auxiliary fueling can operate satisfactorily at part-load with air/fuel ratios of 18 (equivalence ratio $\phi \approx 0.8$, relative air/fuel ratio $\lambda \approx 1.25$). The prechamber stratified-charge flame-jet ignition concepts can operate much leaner than this; however, the best combination of fuel consumption and emissions characteristics is obtained with $\phi \approx 0.9 - 0.75$, $\lambda \approx 1.1 - 1.3$.[70, 71] One performance penalty associated with all these flame-jet ignition concepts is the additional heat losses to the prechamber walls due to increased surface area and flow velocities. The stratified-charge prechamber concepts also suffer an efficiency penalty, relative to equivalent operation with uniform air/fuel ratios, due to the presence of fuel-rich regions during the combustion process.

9.6 ABNORMAL COMBUSTION: KNOCK AND SURFACE IGNITION

9.6.1 Description of Phenomena

Abnormal combustion reveals itself it many ways. Of the various abnormal combustion processes which are important in practice, the two major phenomena are knock and surface ignition. These abnormal combustion phenomena are of concern because: (1) when severe, they can cause major engine damage; and (2) even if not severe, they are regarded as an objectionable source of noise by the engine or vehicle operator. *Knock* is the name given to the noise which is transmitted through the engine structure when essentially spontaneous ignition of a portion of the end-gas—the fuel, air, residual gas, mixture ahead of the propagating flame—occurs. When this abnormal combustion process takes place, there is an extremely rapid release of much of the chemical energy in the end-gas, causing very high local pressures and the propagation of pressure waves of substantial amplitude across the combustion chamber. *Surface ignition* is ignition of the fuel-air mixture by a hot spot on the combustion chamber walls such as an overheated valve or spark plug, or glowing combustion chamber deposit: i.e., by any means other than the normal spark discharge. It can occur before the occurrence of the spark (*preignition*) or after (*postignition*). Following surface ignition, a turbulent flame develops at each surface-ignition location and starts to propagate across the chamber in an analogous manner to what occurs with normal spark ignition.

Because the spontaneous ignition phenomenon that causes knock is governed by the temperature and pressure history of the end gas, and therefore by the phasing and rate of development of the flame, various combinations of these two phenomena—surface ignition and knock—can occur. These have been categorized as indicated in Fig. 9-58. When autoignition occurs repeatedly, during



Normal combustion
A combustion process which is initiated solely by a timed spark and in which the flame front moves completely across the combustion chamber in a uniform manner at a normal velocity.

Abnormal combustion
A combustion process in which a flame front may be started by hot combustion-chamber surfaces either prior to or after spark ignition, or a process in which some part or all of the charge may be consumed at extremely high rates.

Spark knock*
A knock which is recurrent and repeatable in terms of audibility. It is controllable by the spark advance; advancing the spark increases the knock intensity and retarding the spark reduces the intensity.

Surface ignition
hot spots—combustion-chamber deposits
Surface ignition is ignition of the fuel-air charge by any hot surface other than the spark discharge prior to the arrival of the normal flame front. It may occur before the spark ignites the charge (*preignition*) or after normal ignition (*postignition*).

Knocking* surface ignition
Knock which has been preceded by surface ignition. It is not controllable by spark advance.

Run-on
Continuation of engine firing after the electrical ignition is shut off.

Runaway surface ignition
Surface ignition which occurs earlier and earlier in the cycle. It can lead to serious overheating and structural damage to the engine.

Nonknocking surface ignition
Surface ignition which does not result in knock.

Wild ping
Knocking surface ignition characterized by one or more erratic sharp cracks. It is probably the result of early surface ignition from deposit particles.

Rumble
A low-pitched thudding noise accompanied by engine roughness. Probably caused by the high rates of pressure rise associated with very early ignition or multiple surface ignition.

**Knock*: The noise associated with autoignition of a portion of the fuel-air mixture ahead of the advancing flame front. Autoignition is the spontaneous ignition and the resulting very rapid reaction of a portion or all of the fuel-air mixture.

FIGURE 9-58
Definition of combustion phenomena—normal and abnormal (knock and surface ignition)—in a spark-ignition engine. (*Courtesy Coordinating Research Council.*)

otherwise normal combustion events, the phenomena is called *spark-knock*. Repeatedly here means occurring more than occasionally: the knock phenomenon varies substantially cycle-by-cycle, and between the cylinders of a multicylinder engine, and does not necessarily occur every cycle (see below). Spark-knock is controllable by the spark advance: advancing the spark increases the knock severity or intensity and retarding the spark decreases the knock. Since surface ignition usually causes a more rapid rise in end-gas pressure and temperature than occurs with normal spark ignition (because the flame either starts propagating sooner, or propagates from more than one source), knock is a likely outcome following the occurrence of surface ignition. To identify whether or not surface ignition causes knock, the terms knocking surface ignition and nonknocking surface ignition are used. Knocking surface ignition usually originates from preignition caused by glowing combustion chamber deposits: the severity of knock generally increases the earlier that preignition occurs. Knocking surface ignition cannot normally be controlled by retarding the spark timing, since the spark-ignited flame is not the cause of knock. Nonknocking surface ignition is usually associated with surface ignition that occurs late in the operating cycle.

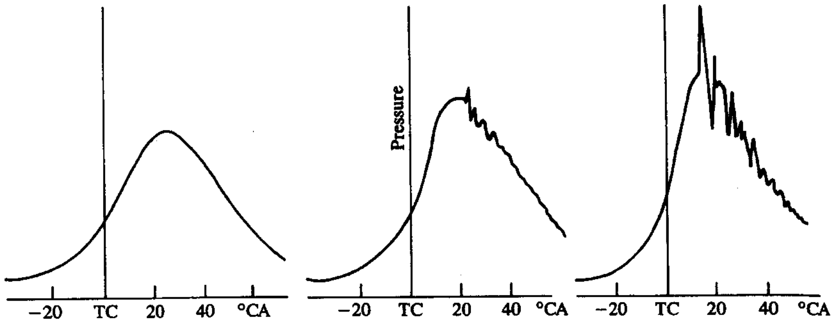
The other abnormal combustion phenomena in Fig. 9-58, while less common, have the following identifying names. Wild ping is a variation of knocking surface ignition which produces sharp cracking sounds in bursts. It is thought to result from early ignition of the fuel-air mixture in the combustion chamber by glowing loose deposit particles. It disappears when the particles are exhausted and reappears when fresh particles break loose from the chamber surfaces. Rumble is a relatively stable low-frequency noise (600 to 1200 Hz) phenomenon associated with deposit-caused surface ignition in high-compression-ratio engines. This type of surface ignition produces very high rates of pressure rise following ignition. Rumble and knock can occur together. Run-on occurs when the fuel-air mixture within the cylinder continues to ignite after the ignition system has been switched off. During run-on, the engine usually emits knocklike noises. Run-on is probably caused by compression ignition of the fuel-air mixture, rather than surface ignition. Runaway surface ignition is surface ignition that occurs earlier and earlier in the cycle. It is usually caused by overheated spark plugs or valves or other combustion chamber surfaces. It is the most destructive type of surface ignition and can lead to serious overheating and structural damage to the engine.[74]

After some additional description of surface-ignition phenomena, the remainder of Sec. 9.6 will focus on knock. This is because surface ignition is a problem that can be solved by appropriate attention to engine design, and fuel and lubricant quality. In contrast, knock is an inherent constraint on engine performance and efficiency since it limits the maximum compression ratio that can be used with any given fuel.

Of all the engine surface-ignition phenomena in Fig. 9-58, preignition is potentially the most damaging. Any process that advances the start of combustion from the timing that gives maximum torque will cause higher heat rejection because of the increasing burned gas pressures and temperatures that result. Higher heat rejection causes higher temperature components which, in turn, can advance the preignition point even further until critical components can fail. The parts which can cause preignition are those least well cooled and where deposits build up and provide additional thermal insulation: primary examples are spark plugs, exhaust valves, metal asperities such as edges of head cavities or piston bowls. Under normal conditions, using suitable heat-range spark plugs, preignition is usually initiated by an exhaust valve covered with deposits coming from the fuel and from the lubricant which penetrates into the combustion chamber. Colder running exhaust valves and reduced oil consumption usually alleviate this problem: locating the exhaust valve between the spark plug and the end-gas region avoids contact with both the hottest burned gas near the spark plug and the end-gas. Engine design features that minimize the likelihood of preignition are: appropriate heat-range spark plug, removal of asperities, radiused metal edges, well-cooled exhaust valves with sodium-cooled valves as an extreme option.[75, 76]

Knock primarily occurs under wide-open-throttle operating conditions. It is thus a direct constraint on engine performance. It also constrains engine efficiency, since by effectively limiting the temperature and pressure of the end-gas, it limits the engine compression ratio. The occurrence and severity of knock depend on the knock resistance of the fuel and on the antiknock characteristics of the engine. The ability of a fuel to resist knock is measured by its octane number: higher octane numbers indicate greater resistance to knock (see Sec. 9.6.3). Gasoline octane ratings can be improved by refining processes, such as catalytic cracking and reforming, which convert low-octane hydrocarbons to high-octane hydrocarbons. Also, antiknock additives such as alcohols, lead alkyls, or an organomanganese compound can be used. The octane-number requirement of an engine depends on how its design and the conditions under which it is operated affect the temperature and pressure of the end-gas ahead of the flame and the time required to burn the cylinder charge. An engine's tendency to knock, as defined by its *octane requirement*—the octane rating of the fuel required to avoid knock—is increased by factors that produce higher temperatures and pressures or lengthen the burning time. Thus knock is a constraint that depends on both the quality of available fuels and on the ability of the engine designer to achieve the desired normal combustion behavior while holding the engine's propensity to knock at a minimum.[74]

The pressure variation in the cylinder during knocking combustion indicates in more detail what actually occurs. Figure 9-59 shows the cylinder pressure variation in three individual engine cycles, for normal combustion, light knock, and heavy knock, respectively.[77] When knock occurs, high-frequency pressure fluctuations are observed whose amplitude decays with time. Figures 9-59*a* and *b* have the same operating conditions and spark advance. About one-third of the cycles in this engine at these conditions had no trace of knock and had normal, smoothly varying, cylinder pressure records as in Fig. 9-59*a*. Knock of varying severity occurred in the remaining cycles. With light or trace knock, knock occurs late in the burning process and the amplitude of the pressure fluctuations



(*a*) Normal combustion, spark 28°BTC
(*b*) Slight knock, spark 28°BTC
(*c*) Intense knock, spark 32°BTC

FIGURE 9-59
Cylinder pressure versus crank angle traces of cycles with (*a*) normal combustion, (*b*) light knock, and (*c*) heavy knock. 4000 rev/min, wide-open throttle, 381-cm^3 displacement single-cylinder engine.[77]

is small (Fig. 9-59*b*). With heavy knock, illustrated here with more advanced spark timing and by selecting an especially high intensity knocking cycle, knock occurs closer to top-center earlier in the combustion process and the initial amplitude of the pressure fluctuation is much larger. These pressure fluctuations produce the sharp metallic noise called "knock." They are the result of the essentially spontaneous release of much of the end-gas fuel's chemical energy. This produces a substantial *local* increase in gas pressure and temperature, thereby causing a shock wave to propagate away from the end-gas region across the combustion chamber. This shock wave, the expansion wave that accompanies it, and the reflection of these waves by the chamber walls create the oscillatory pressure versus time records shown in Fig. 9-59*b* and *c*. Note that once knock occurs, the pressure distribution across the combustion chamber is no longer uniform: transducers located at different points in the chamber will record different pressure levels at a given time until the wave propagation phenomena described above have been damped out.[78]

Many methods of knock detection and characterization have been used. The human ear is a surprisingly sensitive knock detector and is routinely used in determining the octane requirement of an engine—the required fuel quality the engine must have to avoid knock. Knock detectors used for knock control systems normally respond to the vibration-driven acceleration of parts of the engine block caused by knocking combustion pressure waves. A high-intensity flash is observed when knock occurs; this is accompanied by a sharp increase in ionization. Optical probes and ionization detectors have therefore been used. The spark plug can serve as an ionization detector. For more detailed studies of knock in engines, the piezoelectric pressure transducer is the most useful monitoring device. Often the transducer signal is filtered so that the pressure fluctuations caused by knock are isolated.[75]

The amplitude of the pressure fluctuation is a useful measure of the intensity of knock because it depends on the amount of end-gas which ignites spontaneously and rapidly, and because engine damage due to knock results from the high gas pressures (and temperatures) in the end-gas region. Use of this measure of knock severity or intensity shows there is substantial variation in the extent of knock, cycle-by-cycle. Figure 9-60 shows the knock intensity in one hundred consecutive cycles in a given cylinder of a multicylinder engine operating at fixed conditions for knocking operation. The intensity varies randomly from essentially no knock to heavy knock.[79] Cylinder-to-cylinder variations are also substantial due to variations in compression ratio, mixture composition and conditions, burn rate, and combustion chamber cooling. One or more cylinders may not knock at all while others may be knocking heavily.[80]

Since the knock phenomenon produces a nonuniform state in the cylinder, and since the details of the knock process in each cycle and in each cylinder are different, a fundamental definition of knock intensity or severity is extremely difficult. The ASTM-CFR method for rating fuel octane quality (see Sec. 9.6.3) by the severity of knocking combustion uses the time derivative of pressure during the cycle. Cylinder pressure is determined with a pressure transducer. The low-frequency component of pressure change due to normal combustion is filtered out and the rate of pressure rise is averaged over many cycles during the pressure fluctuations following knock. This approach obviously provides only an average relative measure of knock intensity. The maximum rate of pressure rise has been used to quantify knock severity. An accelerometer mounted on the engine can give indications of relative knock severity provided that it is mounted in the same location for all tests. The most precise measure of knock severity is the maximum amplitude of the pressure oscillations that occur with knocking combustion. The cylinder pressure signal (from a high-frequency response pressure transducer) is filtered with a band-pass filter so that only the component of the pressure signal that corresponds to the fluctuations occurring after knock remains. The filter is set for the first transverse mode of gas vibration in the cylinder (in the 3 to 10 kHz range, depending on bore and chamber geometry). The maximum amplitude of pressure oscillation gives a good indication of the severity of knock.[81] The knock intensities in individual cycles shown in Fig. 9-60 were determined in

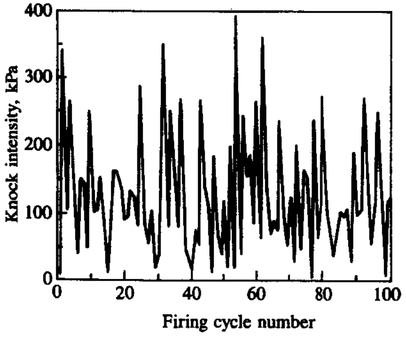


FIGURE 9-60
Knock intensity (maximum amplitude of band-pass-filtered pressure signal) in one hundred individual consecutive cycles. One cylinder of V-8 engine, 2400 rev/min, wide-open throttle.[79]

this manner.[79] Note that because the pressure fluctuations are the consequence of a wave propagation phenomenon, the location of the pressure transducer in relation to the location of the knocking end-gas and the shape of the combustion chamber will affect the magnitude of the maximum recorded pressure-fluctuation amplitude.

The impact of knock depends on its intensity and duration. Trace knock has no significant effect on engine performance or durability. Heavy knock can lead to extensive engine damage. In automobile applications, a distinction is usually made between "acceleration knock" and "constant-speed knock." Acceleration knock is primarily an annoyance, and due to its short duration is unlikely to cause damage. Constant-speed knock, however, can lead to two types of engine damage. It is especially a problem at high engine speeds where it is masked by other engine noises and is not easily detected. Heavy knock at constant speed can easily lead to:

1. Preignition, if significant deposits are present on critical combustion chamber components. This could lead to runaway preignition.†
2. Runaway knock—spark-knock occurring earlier and earlier, and therefore more and more intensely. This soon leads to severe engine damage.
3. Gradual erosion of regions of the combustion chamber, even if runaway knock does not occur.

The engine can be damaged by knock in different ways: piston ring sticking; breakage of the piston rings and lands; failure of the cylinder head gasket; cylinder head erosion; piston crown and top land erosion; piston melting and holing. Examples of component damage due to preignition and knock are shown in Fig. 9-61.[82–84]

The mechanisms that cause this damage are thought to be the following. Preignition damage is largely thermal as evidenced by fusion of spark plugs or pistons. When knock is very heavy, substantial additional heat is transferred to pistons. When knock is very heavy, substantial additional heat is transferred to the combustion chamber walls and rapid overheating of the cylinder head and piston results. Under these conditions, knock is not stable: the overheating increases the engine's octane requirement which in turn increases the intensity of knock. It becomes heavier and heavier, and the uncontrolled running away of this phenomena can lead to engine failure in minutes. This damage is due to overheating of the engine: the piston and rings seize in the bore. The damage due to heavy knock over extended periods—erosion of piston crowns and (aluminum) cylinder heads in the end-gas region—is due primarily to the high gas pressures in this region. Extremely high pressure pulses of up to 180 atm due to heavy knock can occur locally in the end-gas region, in the 5 to 10 kHz frequency range. These high local pressures are combined with the higher-than-normal local surface temperatures which occur with the higher knocking heat fluxes and weaken the material. Pitting and erosion due to fatigue with these excessive mechanical stresses, and breakage of rings and lands, can then occur.[78, 82–84]

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† Note that heavy knock can also remove deposits from the combustion chamber walls, thereby decreasing the octane requirement of the engine.

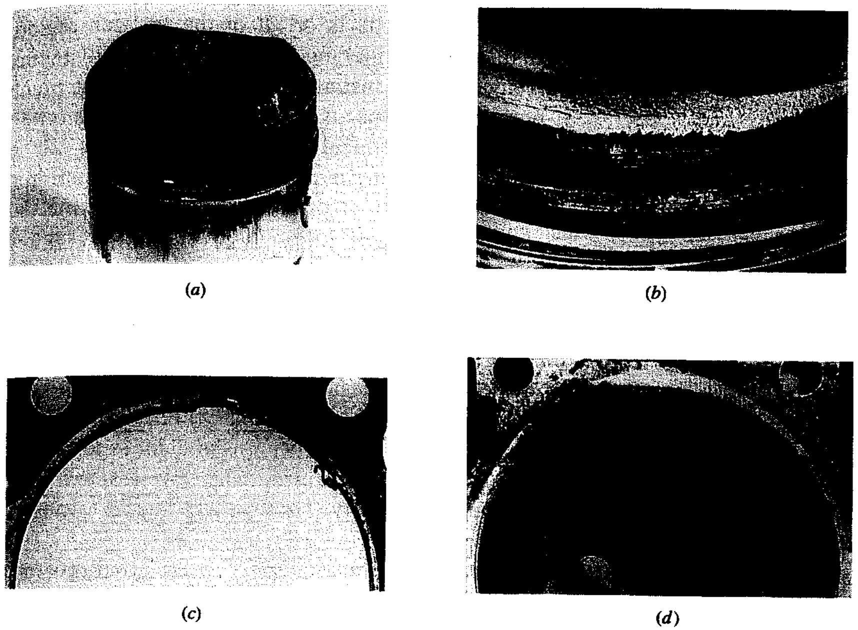

FIGURE 9-61
Examples of component damage from abnormal engine combustion. (a) Piston holing by preignition;[83] (b) piston crown erosion after 10 hours of high-speed knocking;[82] (c) cylinder head gasket splitting failure due to heavy knock;[83] (d) erosion of aluminum cylinder head along the top of the cylinder liner due to heavy knock.[83]

9.6.2 Knock Fundamentals

As yet, there is no complete fundamental explanation of the knock phenomenon over the full range of engine conditions at which it occurs. It is generally agreed that knock originates in the extremely rapid release of much of the energy contained in the end-gas ahead of the propagating turbulent flame, resulting in high local pressures. The nonuniform nature of this pressure distribution causes pressure waves or shock waves to propagate across the chamber, which may cause the chamber to resonate at its natural frequency. Two theories have been advanced to explain the origin of knock: the autoignition theory and the detonation theory. The former holds that 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 preflame chemistry and ending with rapid