Spark plugs

Spark-ignition engine and externally supplied ignition

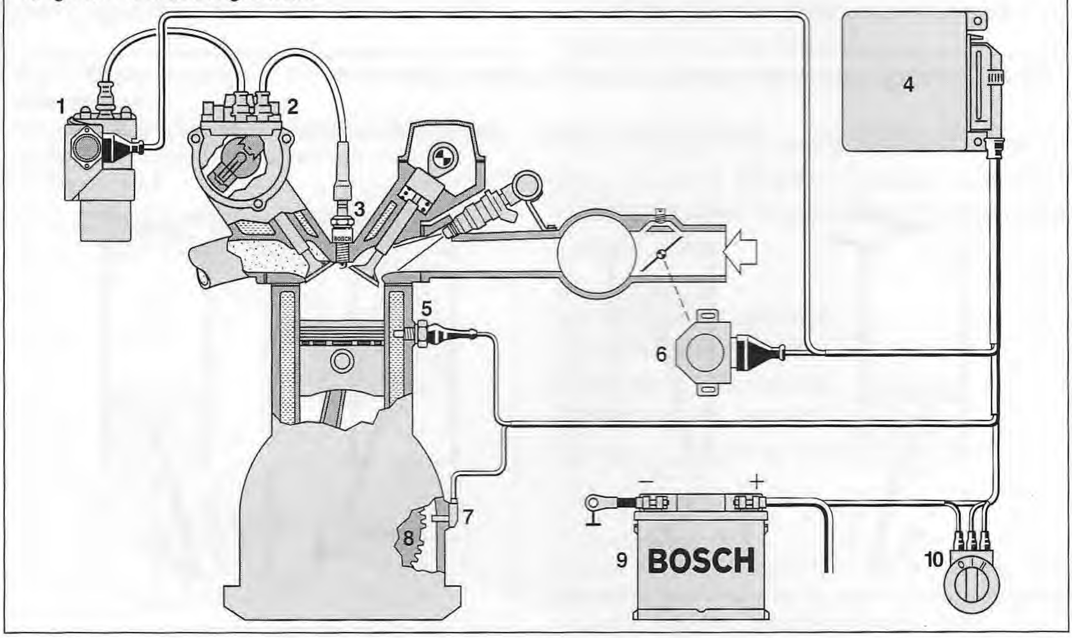
Ignition energy

High-voltage generation
Ignition in the spark-ignition engine is electrical. The electrical energy is taken from the battery. Controlled by the engine, the ignition system periodically generates high voltage. This high voltage causes a spark discharge between the electrodes of the spark plug in the combustion chamber. The energy contained in the spark ignites the compressed air-fuel mixture. The energy taken from the battery is stored in the ignition coil for the periodic generation of high voltage.

This stored energy is used at the right moment in time to generate high voltage. This high voltage is generated inductively in the ignition coil according to the transformer principle. High voltage and ignition energy are sufficient to cover the increase in required ignition voltage resulting from wear in the system (Fig. 1).

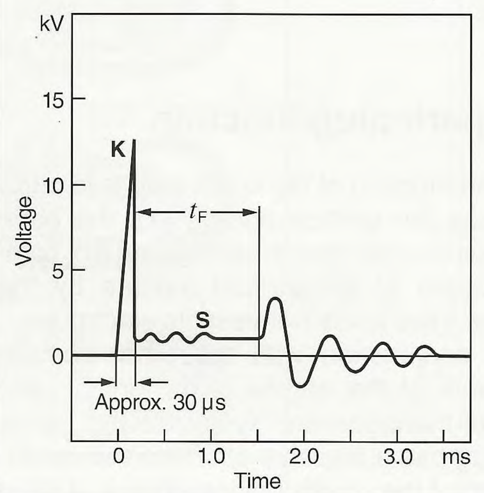
Generation of the ignition spark
If there is sufficient high voltage, the ignition spark jumps across the electrodes of the spark plug. At the instant of ignition, i.e. when the energy-storage device discharges, the voltage across the spark-plug electrodes rises very quickly until the flashover voltage (ignition voltage) is reached. As soon as the spark is discharged, the voltage across the electrode drops to the spark

Fig. 1: Schematic of an electronic ignition system
1 Ignition coil with ignition driver stage, 2 High-voltage distributor, 3 Spark plug, 4 ECU, 5 Coolant-temperature sensor, 6 Throttle-valve switch, 7 Engine-speed sensor, 8 Sensor wheel, 9 Battery, 10 Ignition and starting switch.



voltage. At the same time, a current flows in the now conductive spark gap. The air-fuel mixture is ignited during the burn time of the ignition spark (spark duration). As soon as the conditions required for discharge no longer obtain, the spark breaks off and the voltage decays to zero (Fig. 2). What has been described here applies only if the gas between the electrodes is quiescent. Higher flow velocities lead to a clear change in the spark characteristics.
The spark may be extinguished and reignited in the course of the so-called "spark duration". Phenomena of this kind are known as a follow-up spark.

Fig. 2: Voltage between spark-plug electrodes
K Spark head, S Spark tail,
t_F Spark duration.



Spark duration

Within the "spark duration", ignitable air-fuel mixture must be reached by the spark in order to obtain reliable ignition. The "spark duration" is the length of time for which the arc burns following the initial flashover between the electrodes until the residual stored energy decays. It must be maintained long enough to ensure contact between electrode and combustible mixture, despite any lack of homogeneity in the mixture (inconsistencies in mixture distribution).

Ignition voltage

The ignition voltage required by the spark plug is the maximum high voltage theoretically necessary for spark discharge.
The ignition voltage of the spark plug is the voltage at which the spark actually jumps across the electrodes. The high voltage causes a field strength between the electrodes, so that the spark gap is ionized and thus becomes conductive. The high voltage generated by the ignition system – the available ignition voltage – can exceed 30,000 V. The voltage reserve is the difference between this available ignition voltage and the minimum requirement at the spark plug. The minimum ignition voltage increases as a function of time due to the larger electrode gaps that accompany the aging process. Ignition miss occurs when this process advances to the point where the requirement exceeds the available voltage.

Non-engine-related influences on the ignition-voltage requirement

The following factors determine the spark-plug voltage requirement:
Electrode gap: The minimum ignition voltage increases as a function of increasing spark plug gap.
Electrode configuration: Small electrode dimensions increase the intensity of the electrical field; this enhanced field strength can be employed to reduce the voltage requirement.
Electrode materials: Because the electrodes' electron work function varies according to conductor material, electrode materials influence the ignition voltage.
Insulator surface: If part or all of the electrical transfer between the electrodes is generated along the insulator, electrons from the insulator surface will reduce the ignition voltage.

Engine-related influences on the ignition-voltage requirement

Among the engine design factors that influence the minimum ignition-voltage requirement, compression (boost factor) is the most significant.

Spark-plug stress factors

Spark-plug function

The function of the spark plug is to introduce the ignition energy into the combustion chamber and to initiate the combustion of the air-fuel mixture by the electrical spark between its electrodes.
In conjunction with the other components of the engine, e.g., ignition and fuel-management systems, the spark plug has a decisive effect on the operation of the spark-ignition engine. It must permit reliable cold starting, it must guarantee that there is no misfiring during acceleration, and it must withstand the engine being operated for hours on end at maximum power. These requirements apply throughout the entire service life of the spark plug.
The spark plug is positioned in the combustion chamber at the point most suitable for igniting the compressed air-fuel mixture. It must, under all operating conditions, introduce the ignition energy into the combustion chamber without developing a leak and without overheating.

Design requirements

The spark plug must be designed to withstand extreme operating conditions: The plug is exposed to both the periodic, cyclical variations within the combustion chamber and to the external climatic conditions (Figures 1 and 2).

Electrical demands

When the spark plug is operated with electronic ignition systems, voltages of up to 30,000 V can occur. It is essential that the spark plug resists insulator arcing under these conditions. The deposits resulting from the combustion process, such as soot, carbon residues, ash from fuel and oil additives, will, under certain temperature conditions, conduct electrically. However, under such conditions there must be no arcing or breakdown across the insulator even at the high ignition voltages.
The electrical resistance of the insulator must be sufficient up to 1000°C, with only minimal deterioration in the course of the plug's service life.

Mechanical demands

The spark plug must withstand the pressures (up to approximately 100 bar) occurring periodically in the combustion chamber, whereby it must remain fully gas-tight. In addition, high mechanical strength is required, particularly of the ceramic, which is subjected to mechanical stress when being installed, as well as being stressed in operation by the spark-plug connector and the ignition cable. The spark-plug shell must absorb the tightening forces without suffering permanent deformation.

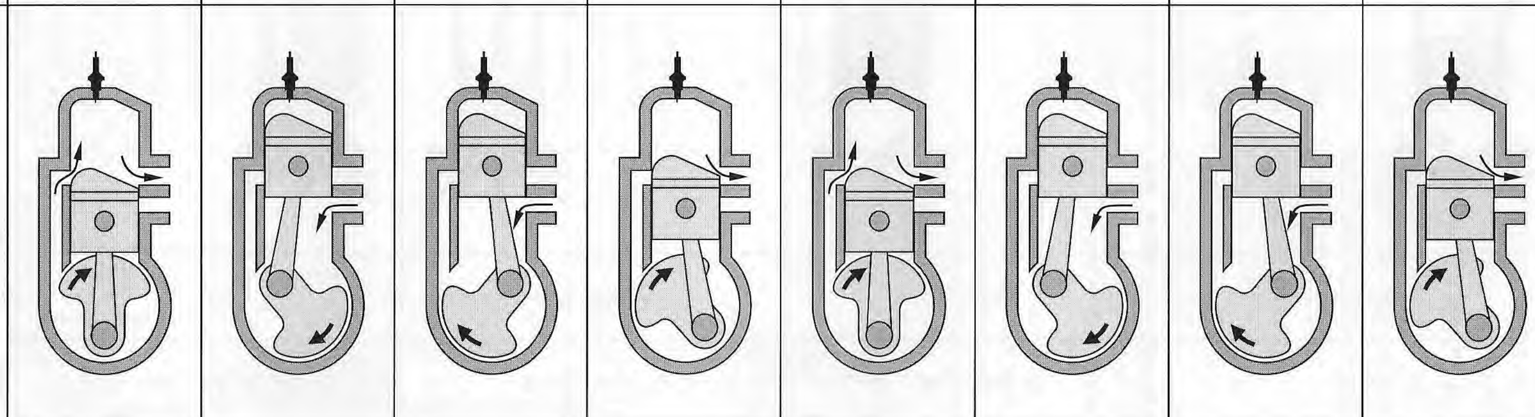
Resistance to chemical stress

The part of the spark plug projecting into the combustion chamber can become red-hot, as well as being exposed to the high-temperature chemical processes taking place inside the chamber. Components in the fuel can form chemically-aggressive deposits on the spark plug, affecting its operating characteristics.

Resistance to thermal stress

During operation, the spark plug, in rapid succession, absorbs heat from the hot combustion gases and is then exposed to the cold air-fuel mixture which is inducted for the next cycle. The insulator must therefore maintain a high level of resistance to thermal shock.
The spark plug must also dissipate the heat it absorbs in the combustion chamber as efficiently as possible to the engine's cylinder head, and the terminal side of the spark plug should heat up as little as possible.

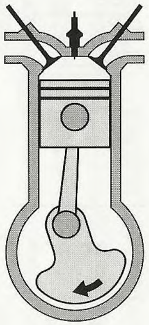
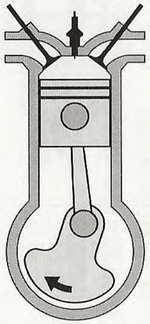
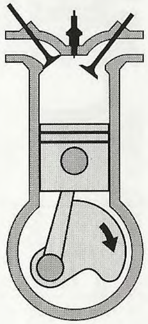
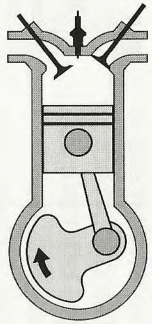
Fig. 1: Pressure and temperature loading of the spark plug in a two-stroke engine

Stroke	Transfer	Compression	Combustion/ power	Exhaust	Transfer	Compression	Combustion/ power	Exhaust
Gas temperature	...120° C	200... 400° C	2000... 2800° C	500... 1200° C	...120° C	200... 400° C	2000... 2800° C	500... 1200° C
Gas pressure	1 bar	5...8 bar	15...30 bar	1...3 bar	1 bar	5...8 bar	15...30 bar	1...3 bar
Piston position								

Crank angle: 0° BDC – 90° – 180° TDC – 270° – 360° BDC – 90° – 180° TDC – 270° – 360° BDC

Crankshaft revolutions: 1 (0°–360°), 2 (360°–360°)

Fig. 2: Pressure and temperature loading of the spark plug in a four-stroke engine

Stroke	Compression	Compression/ power	Exhaust	Induction
Gas temperature	300…600 °C	2000…3000 °C	1300…1600 °C	…120 °C
Gas pressure	8…15 bar	30…50 bar	1…5 bar	0,9 bar
Piston position				

Crank angle 0° 90° 180° 270° 360° 90° 180° 270° 360°

BDC TDC BDC TDC BDC

Crankshaft revolutions 1 2

Spark-plug construction

Components

The spark plug consists of metal, ceramic and glass. These materials have different properties. Appropriate design of the spark plug makes full use of the positive properties of these materials. The terminal stud, insulator, shell and electrodes represent the most important parts of a spark plug. Center electrode and terminal stud are joined by a special conductive glass seal (Fig. 1).

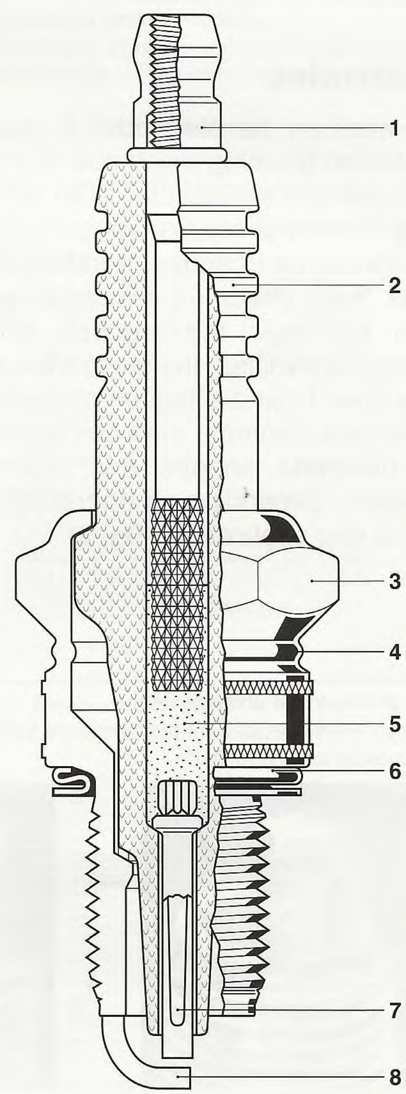
Terminal stud

The steel terminal stud is melted, gastight, into the insulator with a special conductive glass seal which also serves as the electrical connection to the center electrode. On the end projecting out of the insulator, the terminal stud has a thread for attaching the spark-plug connector of the high-voltage ignition cable. In the case of connectors which conform to ISO/DIN Standards a so-called ISO/DIN terminal nut is screwed onto the thread of the terminal stud.

Insulator

The insulator is made of a special ceramic material and its function is to insulate center electrode and terminal stud from the shell. The dense microstructure of the special ceramic ensures high resistance to electrical breakdown (puncture). The surface of the connection side of the insulator is glazed. Moisture and dirt adhere less well to this smooth glazed surface, as a result of which leakage currents are largely prevented. The insulator houses both the center electrode and the terminal stud.
The demands met in spark-plug applications for good thermal conductivity and high insulation resistance are in sharp contrast to the properties of most insulators. The material used by Bosch for the spark-plug insulator consists of aluminum oxide to which small quantities of other materials have been added. After it has been stoved and glazed, this special ceramic satisfies the demands made of the spark-plug insulator for high insulation resistance, good thermal conductivity and both mechanical and chemical strength.

Fig. 1: Construction of spark plug
1 High-voltage connector (terminal nut)
2 Al_2O_3 ceramic insulator
3 Shell
4 Heat-shrinkage zone
5 Conductive glass seal
6 Captive outer gasket
7 Ni/Cu composite center electrode
8 Ground electrode



Shell

The shell is made of steel and its function is to secure the spark plug in the engine's cylinder head. The upper part of the shell has a hexagonal section to which the spark-plug wrench is applied, and the lower part is threaded. The surface of the spark-plug shell has an electroplated nickel coating to prevent corrosion, to keep the thread free and to prevent seizing, the latter point applying particularly in aluminum cylinder heads. Depending on the design of the shell, the spark plug can be provided with a seal ring (captive gasket). After the insulator has been inserted into the spark-plug shell, it is swaged and heat-shrunk in position in one operation by inductive heating under high pressure.

Electrodes

The wear on the electrodes is caused by erosion (burning away due to the ignition sparks) and by corrosion (chemical and thermal attack). These two factors cannot be treated separately as regards their effect on electrode wear. Wear increases the required ignition voltage. In addition, the electrodes must have good heat-dissipation properties.
These requirements may call for different electrode shapes and electrode materials, depending on operating conditions and application (Fig. 2).

Ground electrode

The ground electrode is welded to the shell and usually has a rectangular cross-section. Depending upon the position of the ground electrode relative to the center electrode, a distinction is made between front and side electrodes (Fig. 3). The ground electrode's service life is highly dependent upon its heat dissipation, and on both ground and center electrodes suitable composite materials are employed to improve thermal dissipation and extend effective service life (Fig. 3a). Another factor affecting service life is the ratio of thermally exposed surface to thermally conductive cross-section.
Minimal dimensions, special designs and only partial coverage of the center electrode are all employed to obtain an optimal arc pattern at the ground electrode. The external surfaces and the contours of the areas facing the center electrode can also be designed to enhance performance.

Different spark plugs feature:
- different numbers of ground electrodes, and
- ground electrodes of varying dimensions.

Thicker ground electrodes and multiple electrodes, therefore, can both be used to extend spark-plug service life.

Center electrode

The center electrode of the conventional spark plugs (air gap between insulator nose bore and center electrode) is

Fig. 2: Electrode arrangement
a) Front electrode, b) Side electrodes, c) Surface-gap spark plug without ground electrode (for special applications).

a

b

c

melted, gas-tight, into the insulator with a special conductive seal. The electrode has a slightly smaller diameter than the bore in the insulator nose. This is necessary in order to compensate for the different internal expansion which takes place between the electrode material and the insulator ceramic. The air gap thus produced is subject to very close tolerances and is of great importance with regard to the heat range.
The cylindrical center electrode projects from the insulator nose. Center electrodes made of precious metals are smaller in diameter than the compound electrodes which have a copper core and nickel-alloy jacket.

Electrode gap

The electrode gap is the shortest distance between the center electrode and the ground electrode (Fig. 5). The smaller the electrode gap, the lower the ignition-voltage requirement.
A narrow electrode gap will reduce the voltage required to produce an arc, but the short spark can transfer only minimal energy to the mixture, and ignition miss can result. Higher voltages are required to support an arc across a larger gap. This type of gap is thus effective in transferring energy to the mixture, but the attendant reduction in ignition-voltage reserves increases the risk of ignition miss.
The electrode gap is usually about 0.7...1.2 mm (Fig. 4). The precise optimized electrode gaps for the individual engines are specified by the engine manufacturer and are given either in the owner's manual or in the Bosch spark-plug sales literature.

Electrode shape

Electrode shape affects heat dissipation, resistance to wear, the ignition-voltage requirement and the way the arc is transferred to ignite the mixture.
The electrode shape is dependent on the type of spark gap and the spark position.

Fig. 3: Spark plugs with composite electrodes
a) With front electrode, b) With side electrodes.
1 Conductive glass seal, 2 Air gap, 3 Insulator nose, 4 Composite center electrode, 5 Composite ground electrode, 6 Ground electrodes.

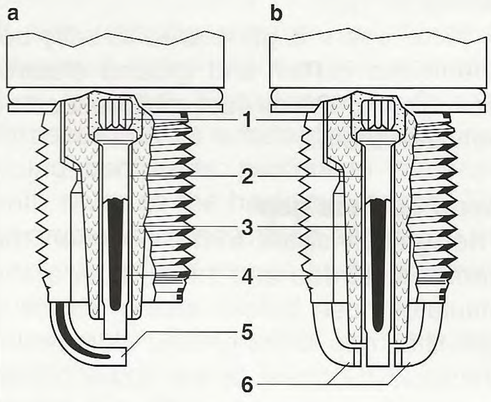


Fig. 4: Relationship between electrode gap and required ignition voltage
U_0 Secondary available voltage, U_Z required ignition voltage, ΔU Ignition voltage reserve.

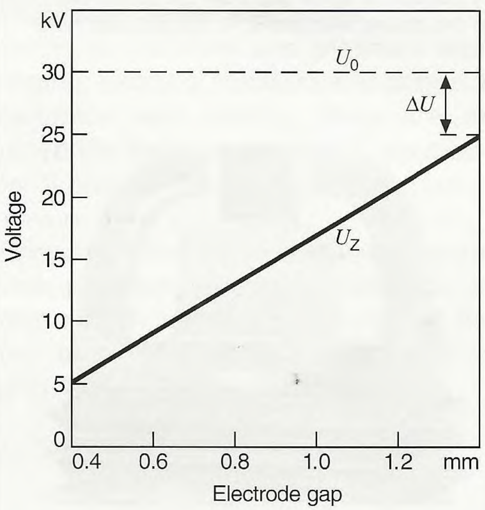
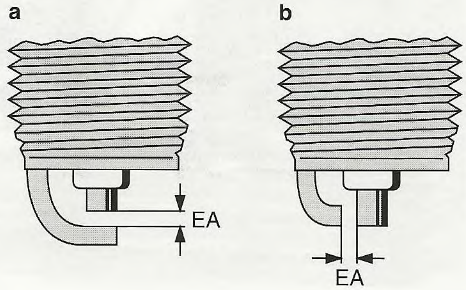


Fig. 5: Electrode gap (EA)
a) Front electrode, b) Side electrode.



Spark gap

The arrangement of the electrodes determines the type of spark gap (Fig. 6).

Spark air gap

A linear spark is generated directly between the center and ground electrodes, igniting the air-fuel mixture located between them.

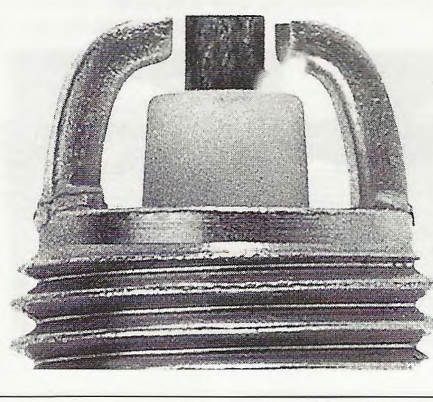
Semi-surface gap

The ignition spark forms between the center electrode and the surface of the insulator nose before arcing across a gas-filled gap to the ground electrode. Because a portion of the spark propagation takes place along this creepage-discharge path, a given ignition voltage produces an arc across larger electrode gaps than with a conventional single-gap design.
These larger gaps can be employed to obtain better ignition patterns.

Fig. 6: Spark gap
a) Air spark gap directly to the ground electrode from the center electrode.
b) Surface/air spark gap from the center electrode to the ground electrodes via the insulator nose.

a

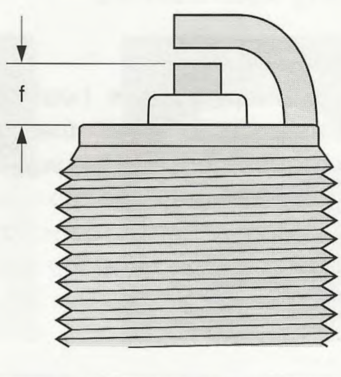
b



Spark position

The spark position is the position of the spark gap in the combustion chamber.
The electric sparks should jump across the point at which the air-fuel mixture flow conditions are particularly favorable. The arrangement of the electrodes and insulator determines from what position the air-fuel mixture is ignited by the electric spark.
The position of the spark f is referred to the front side of the shell (Fig. 7).
The standard spark projection is 3...5 mm, while spark plugs with extreme spark positions are available for special applications. Examples would be spark plugs featuring special spark positions for use in competition and special-purpose engines, in which the actual spark path is inside the spark-plug shell. This substantially reduces the amount of heat absorbed by the spark plug from the combustion chamber, helping to prevent the spark plug from overheating in competition use.

Fig. 7: Spark position (f).



Electrode materials

Compound electrodes

The shunt sensitivity and the corrosion behavior of standard spark plugs with center electrodes made of a nickel-based alloy have been greatly improved by the development of a compound center electrode with a copper core (Fig. 8a).

Pure metals provide better thermal conductivity than alloys. At the same time though, pure metals such as nickel are more sensitive than alloys to aggressive chemical subtances in the combustion gases and to solid deposits.
For this reason, the jacket material of the compound electrode consists mainly of nickel, which is alloyed with chromium, mangangese and silicon. Each of the alloy additions has a special task to perform. Additions of manganese and silicon increase the chemical resistance, particularly against the very aggressive sulphur dioxide (the sulphur comes both from the fuel and from the lube oil).
Nickel-based alloys with silicon, aluminum and yttrium additives also improve resistance to oxidation and scaling.
The ground electrode, which must be flexible enough to allow gap adjustment, can be made of a nickel-based alloy or a composite material.
Such a structure (copper core with nickel jacket) satisfies stringent requirements for high levels of thermal conductivity and corrosion resistance in the ground electrode.

Silver center electrode

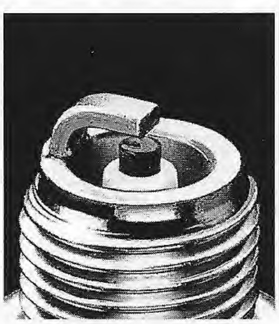
Silver displays the highest electrical and thermal conductivity of any substance. It also features extreme resistance to chemical deterioration when unleaded fuel is used. Resistance to thermal stresses can be substantially enhanced using composite particulate materials with silver as the basic substance. The characteristics described above are the reasons behind its use as an electrode material.
When solid silver is used for the center electrode, this can be reduced in diameter (Fig. 8b).
Despite the reduced diameter, the silver center electrode dissipates heat better than a comparable nickel-based electrode.

Platinum center electrode

Because platinum and platinum alloys display extreme resistance to corrosion, oxidation and melting, they are employed in the manufacture of electrodes for “Long-life” spark plugs.

Presuming the same stresses are applied, platinum electrodes used for any given application can be smaller than the equivalent nickel-based electrode (Fig. 8c).

Fig. 8: Center electrode materials
a) Composite material, b) Silver, c) Platinum.

a


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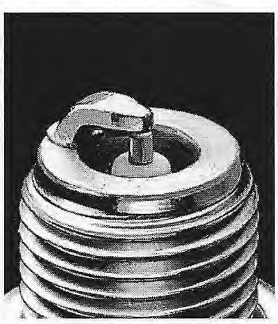

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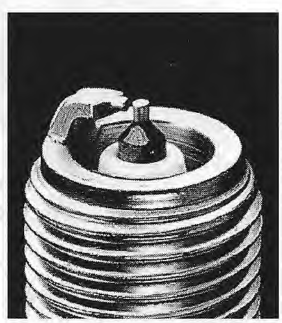


Spark-plug heat ranges

Spark-plug operating temperatures

Operating range

When unleaded fuel is used, the parts of the insulator tip which extend into the combustion chamber should not drop below 500°C – to ensure self-cleaning of the spark plug – and should not exceed approximately 850°C – to prevent auto-ignition (Fig. 1).

Particulate deposits (soot) are produced in the incomplete combustion processes that characterize cold starts. Most of these deposits leave the engine along with the exhaust gases, but some remain to form a coating on both the combustion chamber and the spark plug. As these deposits form on the insulator nose, they can produce a conductive path between the center electrode and the shell. This creepage path absorbs a portion of the ignition energy, thus forming a shunt path and reducing the current available for the ignition spark. Excessive contamination can therefore prevent a spark from being generated (Fig. 2).

The deposition of combustion residues on the insulator nose is greatly dependent on its temperature and takes place mainly below about 500°C. At higher temperatures, the carbon-containing residues on the insulator nose burn-off, as a result of which shunts cannot form, i.e. the plug "cleans" itself. The aim therefore, is to achieve an operating temperature at the insulator nose which is higher than the "self-cleaning limit" of about 500°C, whereby the self-cleaning temperature should be reached as quickly as possible after starting.

The upper temperature limit is about 900°C since above this temperature the air-fuel mixture can ignite prematurely on red-hot parts of the spark plug (auto-ignition). Uncontrolled ignition of this kind is highly detrimental to the engine and may cause irreparable damage within a short space of time.

For these reasons, the operating temperature of the spark plug must be kept within the above-mentioned limits.

Thermal loading capacity

The operating temperature is the equilibrium temperature which is reached be-

Fig. 1: Spark-plug working range
For different engine power outputs, the working range should be between 500 and 850 °C at the insulator.

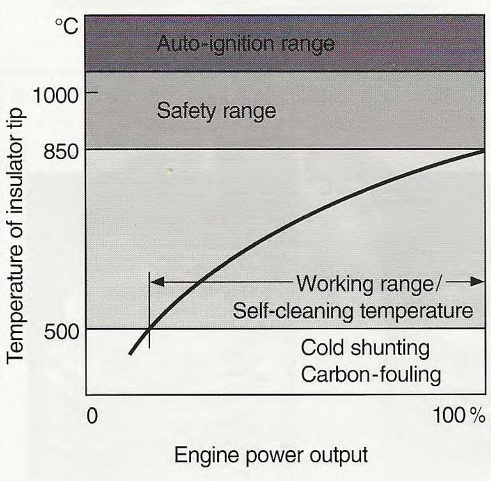
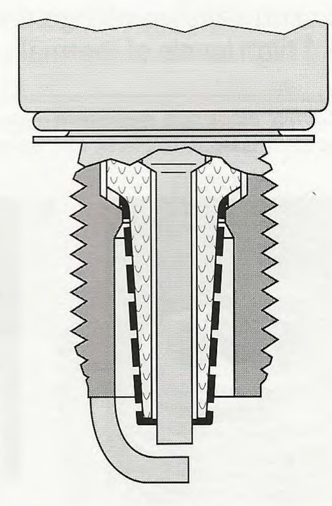


Fig. 2: Shunting due to fouled insulator nose leads to a reduced secondary available voltage
----- Shunt current



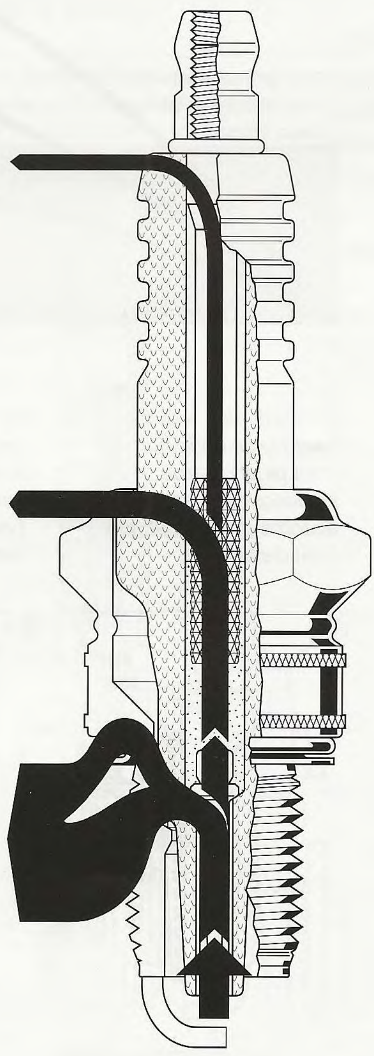
tween heat absorption and heat dissipation. The spark plug is heated by the heat generated during operation in the engine's combustion chamber. The spark-plug shell has more or less the same temperature as the cylinder head, while the temperatures reached by the insulator are considerably higher.

Some (approximately 20 %) of the heat absorbed by the spark plug is dissipated through the inflow of fresh mixture during the induction stroke. Most of the heat is transferred through the center electrode and insulator to the spark-plug shell and from there to the cylinder head (Fig. 3). The supply of heat to the spark plug is dependent on the engine. Engines with a high specific power output usually have higher combustion-chamber temperatures than engines with a low specific power output. The heat-absorbing properties of the spark plug must, therefore, be matched to the engine type in question.
The heat range is characteristic of the thermal loading capacity of the spark plug.

The heat range and the engine

The spark plug's heat range is an index of its capacity to withstand thermal loads. It must be adapted to the engine characteristic.
The different characteristics of automotive engines with respect to operating load, working principles, compression, engine speed, cooling, and fuel make it impossible to run all engines with a standard spark plug. The same spark plug would get very hot in one engine but would reach only a relatively low average temperature in another.
In the first case, the air-fuel mixture would ignite on the glowing parts of the spark plug projecting into the combustion chamber (auto-ignition) and, in the second case, the insulator tip would very soon be so badly fouled by combustion deposits that misfiring would occur due to shunts. In other words, one and the same spark-plug type is not suitable for all engines. To ensure that the plug runs neither too "hot" nor too "cold" in a given engine, plugs with different load capacities were developed. The so-called "heat range", which is assigned to each spark plug, is used to characterise these loading capacities. The heat range is, therefore, a yardstick for selecting the correct spark plug.

Fig. 3 Thermal conduction in the spark plug
A large proportion of the heat absorbed from the combustion chamber is dissipated by thermal conduction (small proportion of cooling of approximately 20 % due to flowpast of fresh A/F mixture is not taken into consideration).

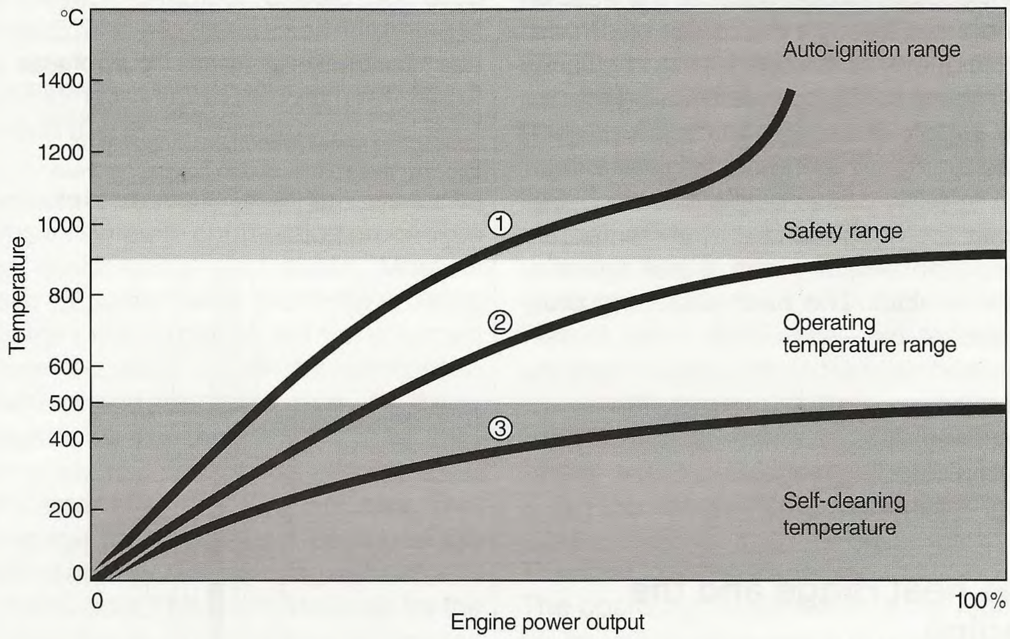


The heat range and the spark plug

Heat range and design

As the above description indicates, each spark plug must be designed to remain within a specific temperature range during operation. Therefore, in order to remain within its operating range, the spark plug for a “hot-running” engine must efficiently dissipate heat acting upon it, while the plug for a “cold-running” engine must retain the heat. Various design factors - with special emphasis on the configuration of the insulator nose – can be applied to adjust the

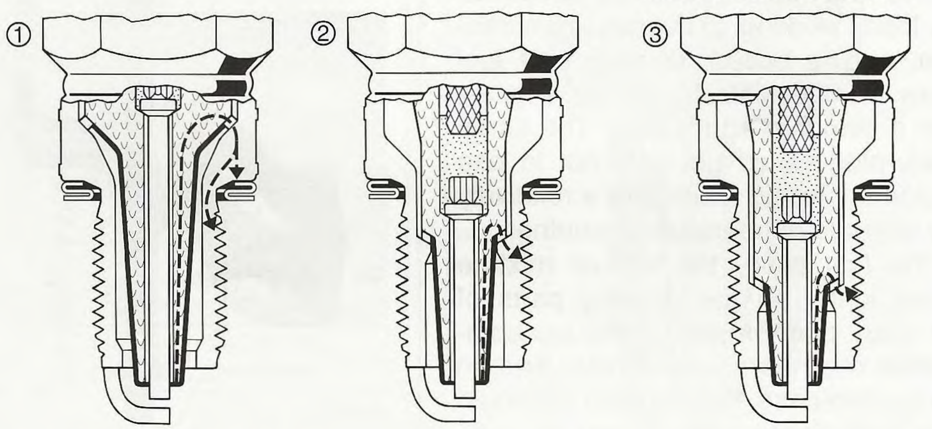
Fig. 4: Temperature curves of spark plugs with different heat-range code numbers
At full load in the same engine.



① Spark plug with high heat-range code number (“hot plug”). Large insulator nose area absorbs much heat, low heat dissipation.

② Spark plug with medium heat-range code number. Insulator nose area smaller than in “hot plug”. Lower heat absorption, better heat dissipation.

③ Spark plug with low heat-range code number (“cold plug”). Smaller insulator nose area absorbs little heat. Very good heat dissipation through short thermal conduction path.



—— Heat-absorbing surface
---- Thermal conduction path

heat range for specific engines and applications.

Influence of insulator nose
Heat absorption is determined by the surface area of the insulator nose. If a large area is exposed to the combustion gases – this is achieved by having a long insulator nose – the insulator nose gets very hot. Conversely, with a short insulator nose, the area is small, and the nose remains cooler.
The heat is dissipated from the insulator nose through the center electrode and through the inner seal ring to the spark-plug shell. If the insulator nose is long, this heat transfer point formed by the seal ring is further away from the hottest point on the insulator nose than is the case with a short insulator nose. Therefore, it follows that spark plugs with a long insulator nose can absorb more heat and dissipate less heat (i.e. they are "hotter") than plugs with a short insulator nose ("cold" plug). Different lengths of insulator nose result, therefore, in different characteristics, in different heat ranges.

Heat-range code number

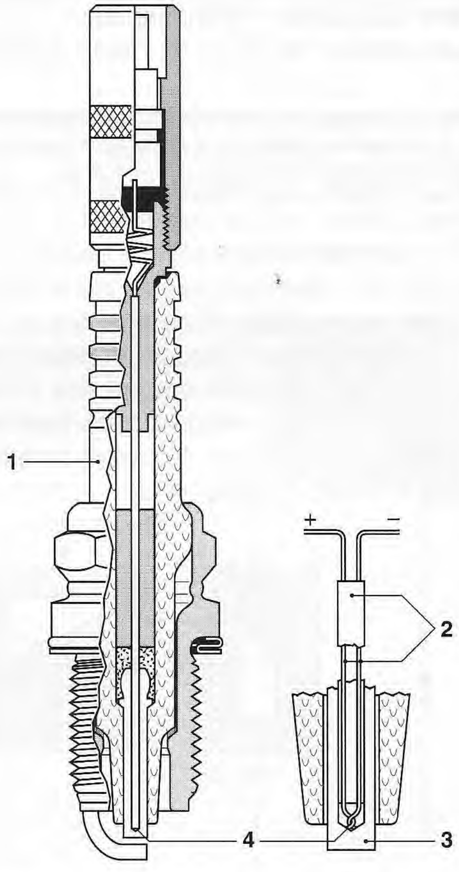
The heat range of a spark plug is identified by a heat-range code number.
A low heat-range code number indicates a "cold plug" with low heat absorption through its short insulator nose.
A high heat-range code number applies to a "hot plug" with high heat absorption through its long insulator nose (Fig. 4).
Heat-range code numbers have been specified to make it easier to differentiate between spark plugs of different heat ranges and to determine the right plug for the engine in question. The heat-range code number is a part of the spark-plug type designation. Low code numbers (e.g., 2...4) signify "cold" plugs. High code numbers (e.g., 7...10) signify "hot" plugs.

Spark-plug selection

Temperature-measuring spark plugs

Bosch works together with the engine manufacturers in determining the best spark-plug design for a given application. The temperature-measuring spark plug provides initial information on the correct choice of spark plug. With a thermocouple in the center electrode of a spark plug, it is possible to record the temperatures in the individual cylinders as a function of engine speed and load.
This expedient represents a simple means of identifying the hottest cylinder and ensuring that the correct spark plug design is selected (Fig. 1).

Fig. 1: Temperature-measuring spark plug
1 Insulator, 2 Sheathed thermocouple,
3 Center electrode, 4 Measuring point.



Ionic-current measuring method

With the ionic-current measuring method, the combustion process is used to specify the heat range. The ionization effect of flames makes it possible, by measuring the conductivity in the spark plug, to evaluate the time curve of the initiation combustion of the air-fuel mixture. This curve shows characteristic changes referred to the thermal loading of a spark plug (Fig. 2).
The advantage of this method over a single temperature measurement in the combustion chamber lies in establishing the probability of ignition, which depends not only on the temperature but also upon the individual engine and spark-plug design parameters.
In order to select the heat ranges of spark plugs, terms and definitions relating to the uncontrolled ignition of air-fuel mixtures have been laid down in accordance with an international agreement (ISO 2542–1972, Fig. 3):
Auto-ignition is taken to mean ignition which is independent of the ignition spark.
If ignition takes place prior to the electrical ignition point, this is pre-ignition.
If it takes place after the ignition point, we speak of post-ignition. Post-ignition is non-critical as regards operation of the engine; conversely, pre-ignition may lead to serious damage. The spark plug must be selected in such a way that there is no pre-ignition.
The ionic-current measuring method makes it possible to select the heat range of a spark plug for any engine and also to measure the heat range in a test engine. In addition, the Bosch ionic-current measuring method makes it possible, by suppressing the ignition spark at certain intervals, to trace post-ignition and its percentage share in relation to the suppression rate as the combustion-chamber temperature rises (by advancing the ignition-timing Fig. 4).
A change in the ionic-current trace on the screen permits the precise determination, even without suppressing the electric ignition spark, of the transition from post-ignition to incipient pre-

Fig. 2: Diagram of ionic-current measurement
1 From ignition distributor, 2 Ionic-current adapter, 2a Break-over diode (BOD), 3 Spark plug, 4 Ionic-current device, 5 Oscilloscope.

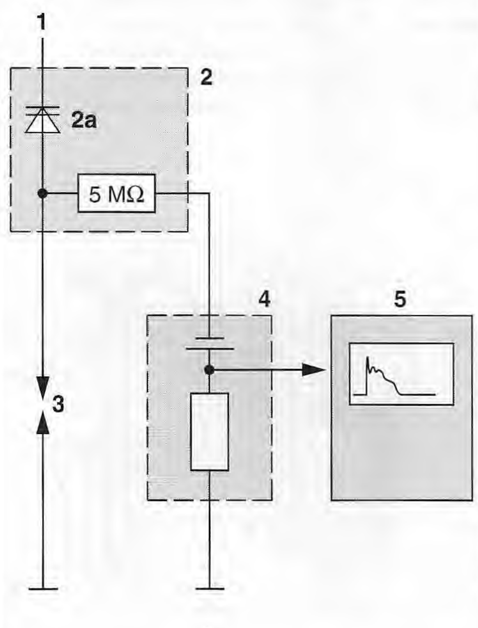
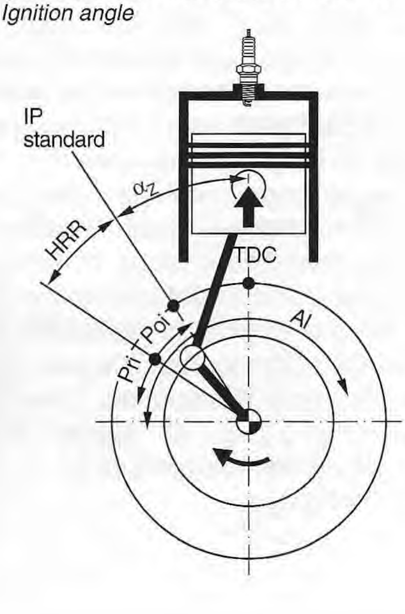


Fig.3: Definitions with regard to heat-range selection
AI *Auto-ignition,* TDC *Top dead center*
Pri *Pre-ignition,* Poi *Post-ignition*
HRR *Heat-range reserve in °crankshaft*
IP *Ignition point in °crankshaft before* TDC
α_z *Ignition angle*



ignition. This makes the measuring method an additional aid in evaluating individual design parameters with regard to their tendency to produce auto-ignition under maximum loading.
The practical procedure is now explained with reference to an example: ionic-current measurement on three Bosch spark plugs with different heat ranges, under full-load operation, $n = 5000\,\text{min}^{-1}$, ignition timing factory-set .

Ionic current testing (example):

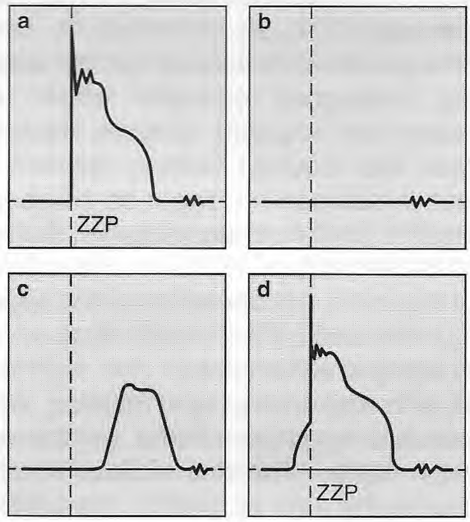
Spark plug series with heat range	% POST¹)	PRE²)
WR9DC	100	ja
WR8DC	50	0
WR7DC	0	0

¹) POST = post-ignition
²) PRE = pre-ignition

The spark plug with the highest heat-range code number shows 100 % post-ignition even with the factory-set ignition timing, i.e. each time the spark is suppressed, the compressed mixture is still ignited by the excessive heat at the insulator. Isolated cases of pre-ignition can also occur. Even the intermediate-range spark plug produces ignition every second time the current is suppressed - the safety reserves are still inadequate.
The spark plug with the lowest heat range promotes neither pre- nor post-ignition - the temperature of the insulator nose remains low enough to remove the danger of auto-ignition. This would be the recommended spark plug in this example.
Because the spark plug can be two heat ranges higher before pre-ignition occurs, the heat range safety margin is adequate.
The above remarks illustrate that spark plugs cannot simply be selected from a catalog and installed.
Spark plug specifications are generally determined in a process that includes close cooperation between engine and spark-plug manufacturers. The recommendations of the vehicle manufacturer and the recommendations – including alternate heat ranges for different regions – contained in the Bosch sales catalogues should always be observed.
Application measurements on spark plugs are best performed on the engine test stand or chassis dynamometer.
Since the engine must be operated at full load over lengthy periods of time in order to establish the hottest operating point, it is not possible to conduct tests on public roads.

Fig. 4: Characteristic ionic-current oscilloscope patterns
a) Normal operating conditions,
b) Suppressed ignition without post-ignition,
c) Suppressed ignition with post-ignition,
d) Pre-ignition.

ZZP = Ignition point



Operating behavior of spark plug

Changes during operation

During operation, the spark plug is subjected both to wear and to fouling and must, therefore, be replaced at regular intervals.
In the course of its service life, the spark plug undergoes changes which increase the required ignition voltage. When the required voltage reaches a value which can no longer be compensated for by the voltage reserve, the result is misfiring.
Furthermore, the operation of the spark plug can also be adversely affected by the aging of the engine.
Deposits can lead to heat tracking, with attendant negative effects on the ignition flame. The immediate results assume the form of ignition miss, leading to a substantial increase in exhaust emissions followed by damage to the catalytic converter.

Engine-related influences

As the engine ages, leakage may occur which leads to a higher content of oil in the combustion chamber. This results in heavy deposits of soot, ash and oil carbon on the spark plug and may lead to shunts. The result is misfiring.

Electrode wear

Characteristics

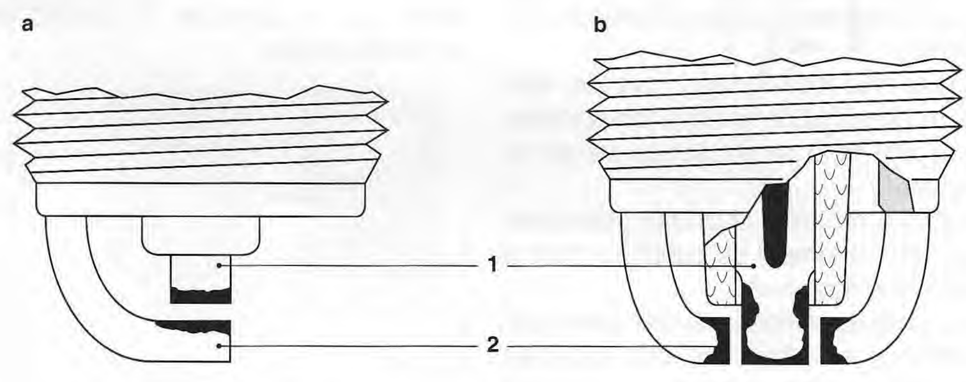
Electrode wear is the removal of material from the electrodes.
A visible sign of electrode wear is the increase in the electrode gap during the plug's service life. Electrode wear can be minimized through careful selection of shapes, materials and gap configuration (surface-air gap) for the electrode.

Two processes contribute to electrode wear:
- spark erosion, and
- corrosion in the combustion chamber.

Spark erosion and corrosion

The discharge of electrical sparks leads to an increase in the temperature of the electrodes. In conjunction with the aggressive combustion gases, there is clear wear at high temperatures. Melted-open, microscopically small sur-

Fig. 1: Wear at center and ground electrodes
a) Front-electrode spark plug, b) Side-electrode spark plug.
1 Center electrode, 2 Ground electrode.



face areas are oxidized or react with other constituents in the combustion gases. The result is a removal of metal, which can be seen in the rounding of edges and also in the widening of the electrode gap (Fig. 1).

Heat-resistant materials – such as the noble metal platinum – can be used to minimize electrode wear.

Abnormal operating conditions

Abnormal operating conditions can irreparably damage the engine and the spark plug. These include:
- auto-ignition,
- knocking and
- high oil consumption (formation of ash and carbon residue).

Engine and spark plug may be damaged also by an incorrectly tuned ignition system, the use of spark plugs with the wrong heat range for the engine, or the use of unsuitable fuels.

Auto-ignition

Full-throttle operation can generate localized hot spots and cause auto-ignition at the following locations:
- at the tip of the spark plug's insulator nose,
- on the exhaust valve,
- on protruding sections of the head gasket, and
- on loose deposits.

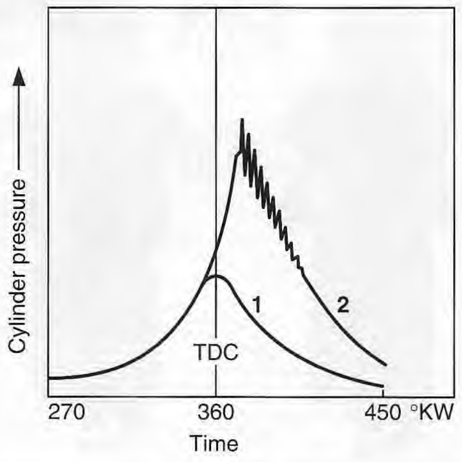
Auto-ignition is an uncontrolled ignition process in which the temperatures in the combustion chamber can rise to such an extent as to cause serious damage to the engine and the spark plug.

Knocking

Knocking is uncontrolled combustion with a very steep rise in pressure. It is caused by the spontaneous ignition of portions of the mixture which have not yet been reached by the advancing flame front triggered by the ignition spark. Combustion takes place considerably faster than normal (gentle) combustion. Pressure oscillations occur, with high peak pressures and high frequencies which are superimposed on the normal pressure curve (Fig. 2).
As the high-pressure waves hit the walls of the combustion chamber, their impact produces a metallic knocking sound.
The engine is subjected to severe mechanical stressing as a result of the high-pressure waves. The following engine components are endangered in particular:
- Cylinder head
- Spark plugs
- Pistons

Failure to recognize and deal with pre-ignition will inevitably lead to serious engine damage. The damage is similar to that associated with the cavitation damage that occurs when supersonic flow patterns are generated. On the spark plug, pitting on the ground electrode's surface is the first sign of pre-ignition.

Fig. 2: Pressure in the cylinder
1 With normal combustion,
2 With knocking.



Types of spark plug

Seat

Depending on the type of engine, the seal between the spark plug and cylinder head is by means of a flat seat or a conical seat (Fig. 1).
The flat-seat version uses a captive gasket on the spark-plug shell as a sealing element. It is specially shaped and provides a permanently elastic seal if correctly mounted.
With the conical seat, without the use of a gasket, a conical surface of the spark-plug shell seals directly on a mating surface of the cylinder head.

Special spark plugs

Special-purpose spark plugs are available for unusual applications. These plugs are distinguished by the special design features used to adapt them to the operating and installation environment in a particular engine.

Spark plugs for motor racing

Due to their constant operation at full load, engines for racing vehicles are exposed to very high thermal loading. Spark plugs for these operating conditions usually have electrodes which are manufactured from precious metals (silver, platinum) and a short insulator nose. As a result of their short insulator nose, the heat absorption of these plugs is very low and heat dissipation through the precious-metal electrodes is high.

Spark plug with resistor

By means of a resistor fitted in the path to the spark gap of the spark plug, it is possible to reduce the transmission of the interference pulses to the high-tension ignition cables, with the result that the interference radiation is also reduced. Low current in the initial arcing phase also helps reduce electrode erosion. The resistor is formed by the special conductive seal between the center electrode and the terminal stud. The required resistance of the special seal is achieved by the selection of appropriate admixtures.

Fully-shielded spark plug

In cases where very high demands are placed on interference suppression (radios, car telephone), it may be necessary to shield the spark plug.
In fully-shielded spark plugs, the insulator is surrounded by a metal sleeve. The connection is inside the insulator. The shielded H.T. ignition cable is fastened onto the sleeve by means of a union nut. Fully-shielded spark plugs are watertight (Fig. 2).

Fig. 1: Flat seat with captive gasket (left), and conical seat without gasket (right)

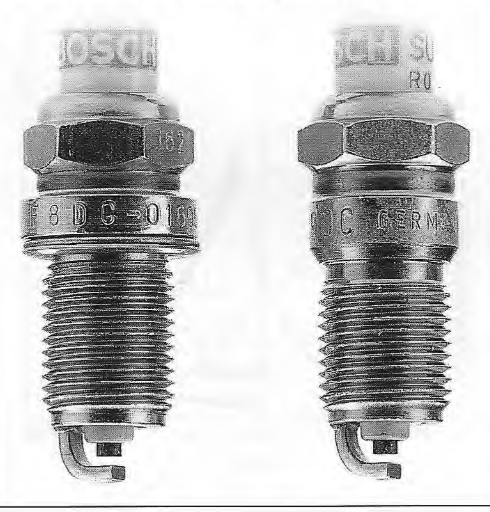
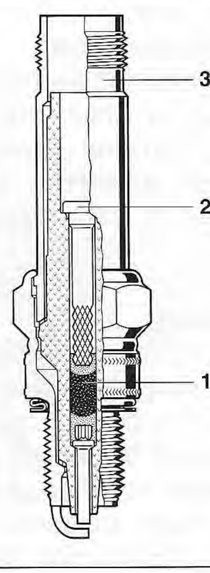


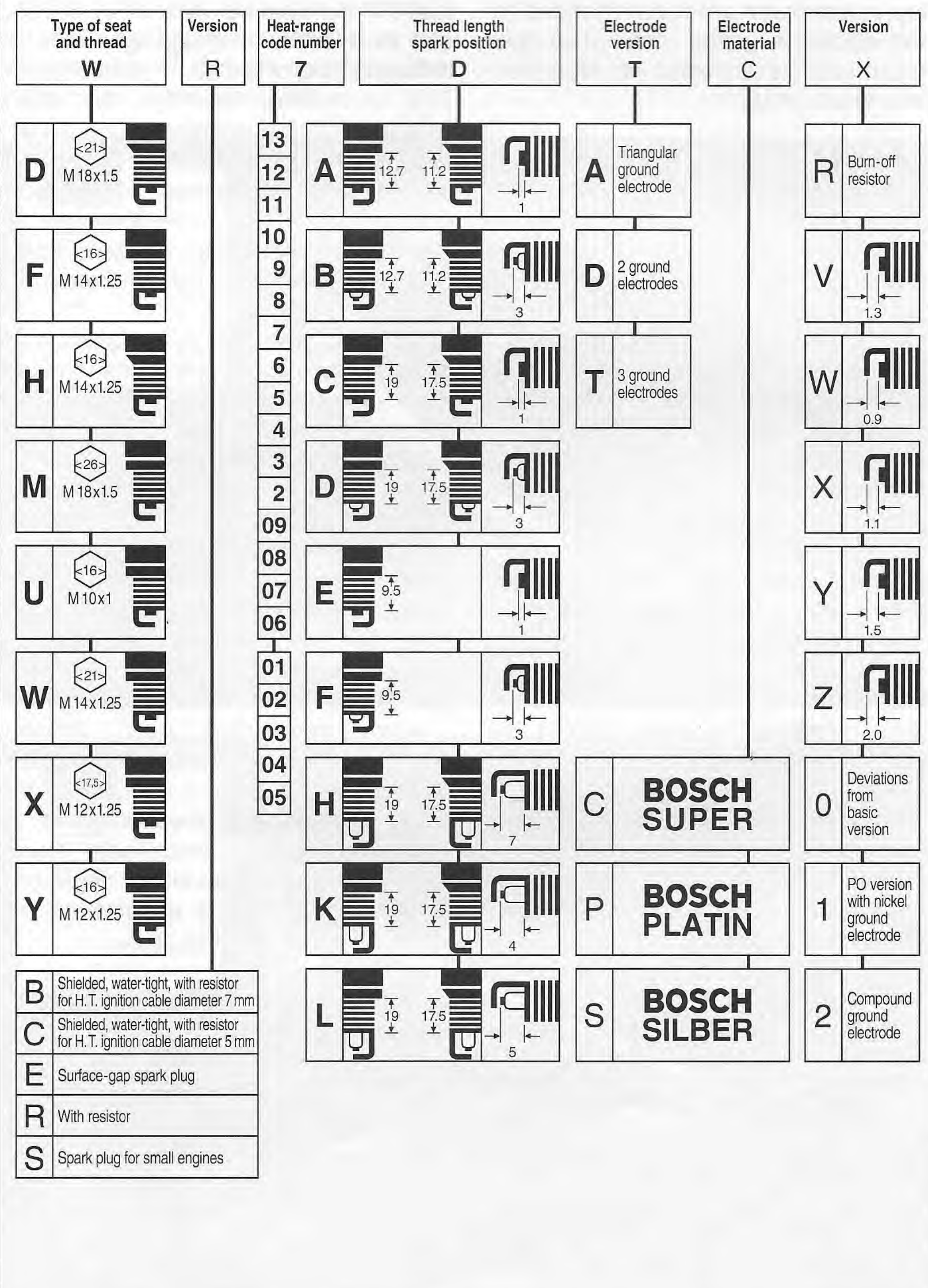
Fig. 2: Fully-shielded spark plug
1 Special conductive glass seal (interference-suppression resistor),
2 Ignition-cable connection,
3 Shield sleeve.



Type designation

The identification of the types of spark plug is by means of a specific type designation (Fig. 3). This type designation contains all the important features of the spark plug with the exception of the electrode gap which is given additionally on the spark-plug packaging. The correct spark plug and electrode gap for the respective engine is specified by the engine manufacturer or is recommended by Bosch.

Fig. 3: Type designation code for Bosch spark plugs (Dimensions in mm)



In practice

Fitting the spark plug

If the correct type is selected and correctly fitted, the spark plug is a reliable part of the ignition system.
Gap adjustments are recommended for front-electrode plugs only. The gap should not be adjusted on side-electrode spark plugs.

Removal

When removing the spark plug, first of all unscrew by a few turns. Then, using compressed air, or a brush, clean the surrounding area in the cylinder head so that no dirt gets into the thread of the cylinder head or into the combustion chamber when the spark plug is removed. Only then screw out the spark plug completely.
If the spark plug is very tight, unscrew it only a little, so as not to damage the thread in the cylinder head. Then drip oil or penetrating oil onto the threads, screw the spark plug back in again and attempt after a few minutes to unscrew it completely.

Installation

When installing the spark plug in the engine, note the following:

– The contact faces on the spark plug and on the engine must be clean.
– Bosch spark plugs are treated with an anti-corrosion oil, so no supplementary lubricants are required. Seizing up is impossible because the threads are nickel-plated.
Spark plugs should, if possible, be tightened to the torque given in Table 1 using a torque wrench. When the spark plug is tightened, the tightening torque is transmitted from the hexagon section to the seat and the thread.
This means that the insulator may come loose if the spark-plug shell is warped due to excessive tightening torque or through tilting of the spark-plug wrench. This completely destroys the spark plug's thermal properties; such a plug can cause engine damage. Therefore, the tightening torque must not exceed a given value.
The tightening torques apply to spark plugs as new, i.e. to lightly oiled spark plugs.
In practice, spark plugs are often fitted without a torque wrench. Consequently, they are usually overtightened. Bosch therefore recommends the following rule-of-thumb procedure:

1. Screw the spark plug by hand into the clean thread as far as it will go. Then apply the spark-plug wrench. One of three procedures is now used:
– If you are installing new flat-seal spark plugs, turn an additional 90° after you first encounter resistance (Fig. 1),
– when re-installing used flat-seal spark plugs, the additional torquing angle corresponds to 5 minutes on the clock, or an angle of about 30°,
– when installing conical-seat plugs, turn the wrench by addiional angle corresponding to 2 to 3 minutes on the clock, or about 15° (Fig. 2).

Table 1. Tightening torques

Cylinder-heat material	Thread	Cast iron Tightening torque N · m	Light alloy Tightening torque N · m
Spark plug with flat seat	M 10x1	10...15	10...15
	M 12x1.25	15... 25	15...25
	M 14x1.25	20... 40	20...30
	M 18x1.5	30... 45	20...35
Spark plug with conical seat	M 14x1.25	20...25	15...25
	M 18x1.5	20...30	15...23

2. When tightening or loosening the spark plug, the wrench should not be held at an angle; the insulator will otherwise be broken off or pushed to the side, and the spark plug destroyed.
3. In the case of box wrenches with a loose tommy bar, the hole for the tommy bar must be above the spark plug so that the tommy bar can be pushed through both holes in the box wrench. If the holes are lower and the tommy bar is inserted only through one hole, the spark plug will be damaged.

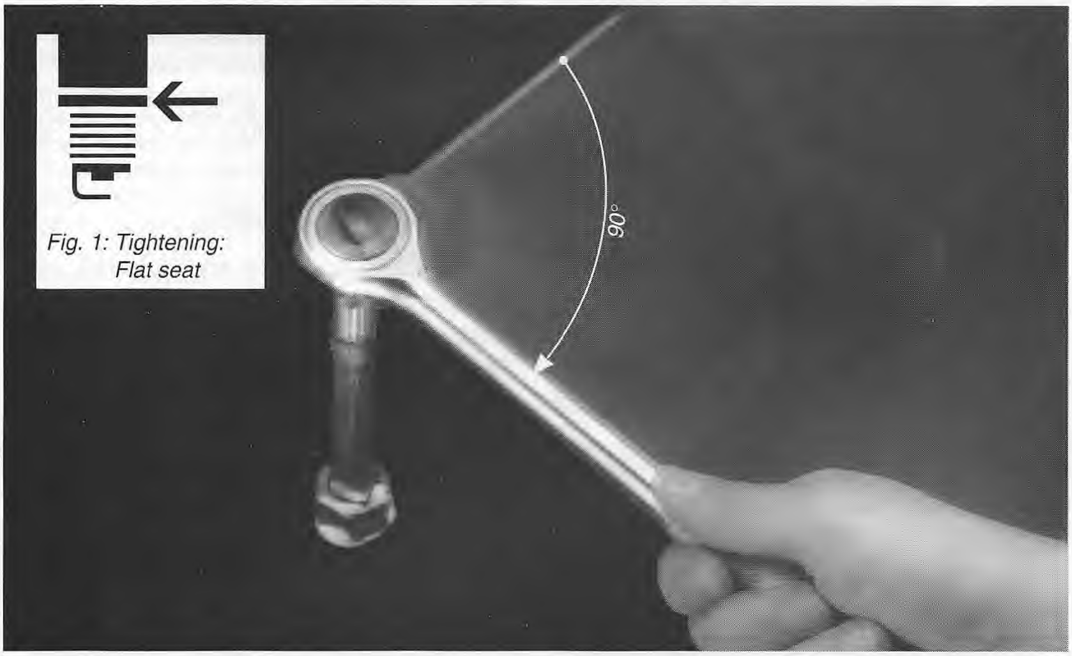


Fig. 1: Tightening: Flat seat

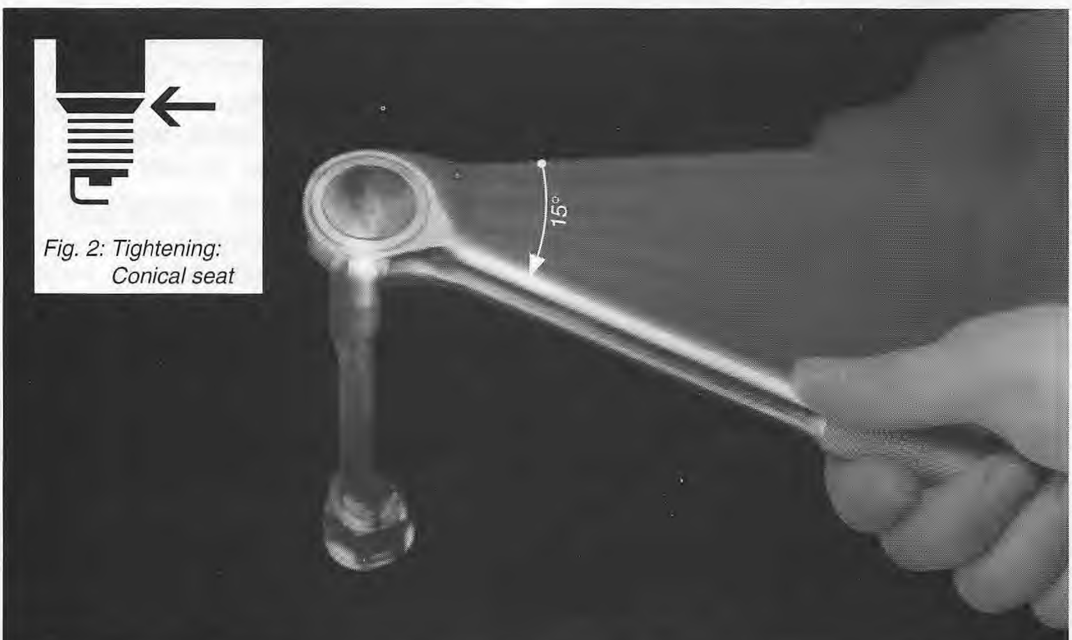


Fig. 2: Tightening: Conical seat

Mistakes and their consequences

Basically, a given engine type should be fitted only with the spark plugs specified by the engine manufacturer or with those recommended by Bosch. To rule out incorrect selection from the outset, the motorist should consult the Bosch Service specialist. The desired information is also provided in sales literature, such as catalogs, product stands with information boards or application summaries. The use of unsuitable types of spark plugs can lead to serious engine damage. The most frequently encountered mistakes are:
– incorrect heat range,
– incorrect thread length, and
– modifications/damage to seal face.

Incorrect heat-range code number
The heat-range code number must, under all circumstances, conform to the spark plug specifications of the motor-vehicle manufacturer or to the Bosch spark-plug recommendations.
Spark plugs with the wrong heat range for the engine can produce auto-ignition.

Incorrect thread length
The length of the thread on the spark plug must be the same as the length of the thread in the cylinder head.
If the spark-plug thread is too long, the spark plug projects too far into the combustion chamber.
Consequences:
– possible damage to the piston,
– coking-up of the spark-plug thread may make it impossible to remove the spark plug,
– spark plug overheating.
If the thread is too short, the spark plug does not project far enough into the combustion chamber.
Consequences:
– poor ignition of the mixture,
– spark plug does not reach its self-cleaning temperature,
– the lower threads in the cylinder head become coked up.

Modifications to the seat
On spark plugs with a conical seat, it is not permissible to use a washer or a seal ring. On flat-seat spark plugs, it is permissible to use only the captive gasket fitted to the spark plug. It must not be removed or replaced by a washer.
Without the gasket, the spark plug projects too far into the combustion chamber. This impairs efficient heat transfer between spark-plug shell and cylinder head, and the plug does not seal properly.
If an additional seal ring is used, the spark plug is not seated deep enough in the thread hole, and the transfer of heat from the spark-plug shell to the cylinder head is also impaired.

Spark-plug faces

Reading the spark plugs provides valuable information on spark-plug and engine operating conditions.
The appearance of the electrodes and insulator of the spark plug – the "spark-plug face" – provides information on spark-plug operation, mixture and the combustion process within the engine (Figures 3 to 5).

Reading the spark plugs is thus an important engine-diagnosis procedure. For an accurate reading, observe the following procedural guidelines: The vehicle must be operated under standard conditions before an attempt is made to read the spark plugs. If the reading is preceded by an extended period at idle, carbon deposits on the plug will render accurate analysis impossible; this problem is more serious immediately after a cold start. The vehicle should be driven about 10 km, at a variety of moderate loads and engine speeds. Extended idling prior to shutdown is to be avoided.

I have ommitted spark plug faces as this Tech manual was printed before Unleaded came into use.