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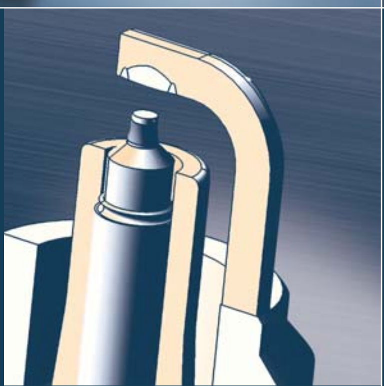

New Spark Plug Concepts for Modern-day Gasoline Engines

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New Spark Plug Concepts for Modern-day Gasoline Engines

The development of gasoline engines is following the trend of lower fuel consumption allied to lower emissions and enhanced driving enjoyment. Modified combustion systems and small, supercharged engines are the consequence. This is resulting in new demands being placed on the ignition system, especially the spark plug. This article by BERU sets out the state of the art and looks at prospective future solutions.

1 Introduction

Gasoline engine technology is on the move. For a long time developments were dominated by naturally-aspirated engines with intake manifold fuel injection and controlled three-way catalytic converters. We are currently in a phase of major change. The key driver of these developments is the demand for lower fuel consumption and emissions. Partly variability in the valve drive based on phasers or valve lift control as well as direct injection systems with wall or air guided combustion have already been introduced into mass production [1].

The latest generation of fuel injection systems featuring piezo-controlled injectors, an outward opening conical jet nozzle, multiple injection and jet-guided mixture formation is extending [2] the range of unchoked [3], lean-burn engine operation and translating reduced charge cycle losses into consumption benefits. The position of the injector between the valves is comparable to the layout in state of the art diesel engine. The spark gap is shifted into the tapered surface area of the injection jet [4], resulting in the key demands in terms of smaller designs, positioned ground electrode and more precise spark location positioning, **Figure 1**.

There is also a trend toward downsizing with supercharging. Turbochargers with variable turbine geometry or two-stage charging are deployed in top-of-the-range engine variants. The increased charge density results in a higher ignition voltage requirement, which – especially with slimmer spark plugs – poses greater demands in terms of the dielectric and mechanical properties of the spark plug ceramic.

Based on the example of the development of a new BERU M12 spark plug, the following presentation illustrates how the new demands can be met by means of modified design, material selection and application.

2 State of the Art

The principal requirements – reliable ignition, adequacy for cold starting and repeat starting, and high mileage – can be met by a variety of spark plug concepts [5]. Combustion quality, cold starting, service life and cost factors are key to the choice of concept.

2.1 Low-cost Concepts

Nickel alloy based electrodes are common solutions in this segment. Depending on the engine requirements, single or multiple electrodes, in air and/or surface gap configuration, are deployed to improve cold starting. The modest cost means compromises must be made in terms of service life.

2.2 High-end Concepts

Different platinum or iridium based noble metal alloys on the electrodes are used in this segment. Similarly to the low-cost spark plugs, there are various electrode layouts and spark gap configurations. The higher cost is justified by outstanding durability.

3 Requirements for New Spark Plug Generations

The new direct fuel injection systems mean that there is less room for the spark plug in the cylinder head. This means the thread has to be made longer and/or the spark plug geometry has to be modified. M12 spark plugs are in widespread use, though they provide less ceramic wall thickness than conventional M14 spark plugs.

In addition, the downsizing engine concepts featuring supercharging, and the resultant increase in charge density, means

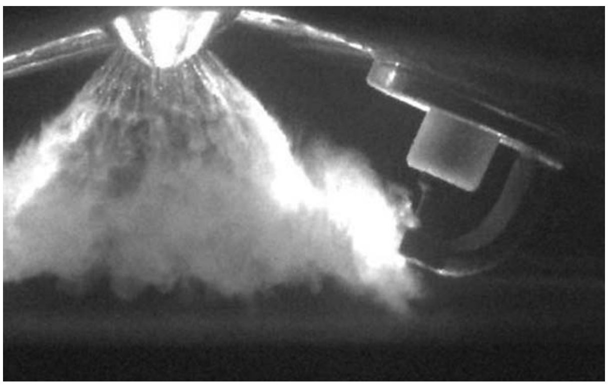

Figure 1: Matching of spark plug to injection jet in gasoline direct injection engine (photo: Daimler-Chrysler)

Authors

Dr. Manfred Adolf
is Head of Development Ignition Technology at BERU AG in Germany.

Thomas Alban
is responsible for Production Process Management at BERU AG in Germany.

Dipl.-Ing. Hans Houben
Vice President Research & Development at BERU AG in Germany.

Dipl.-Ing. (FH) Martin Knoch
is employee for advanced development at BERU AG in Germany.

Werner Niessner
is Head of Spark Plug Development at BERU AG in Germany.

Dipl.-Ing. (FH) Ulrich Stockmeier
is employee for Ignition System Application at BERU AG in Germany.

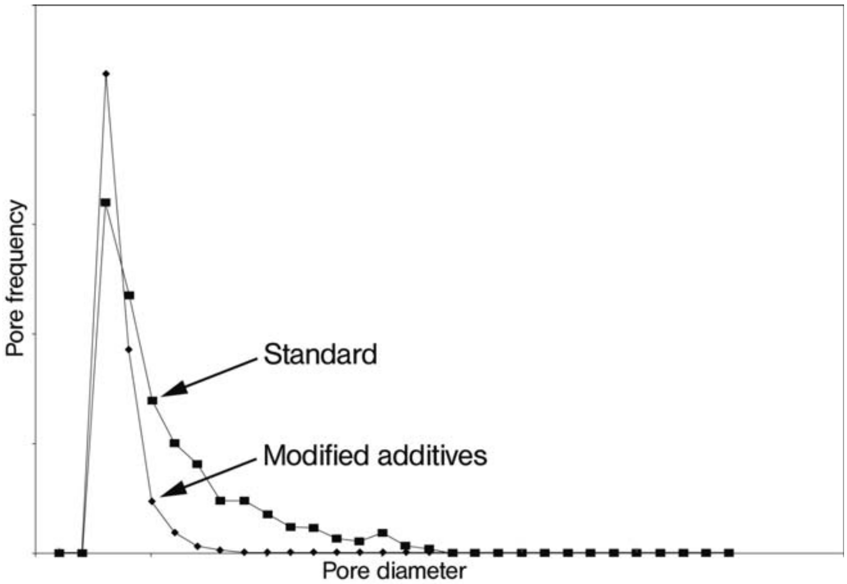

Figure 2: Modifying the organic additives enables a substantially reduction of pore diameter

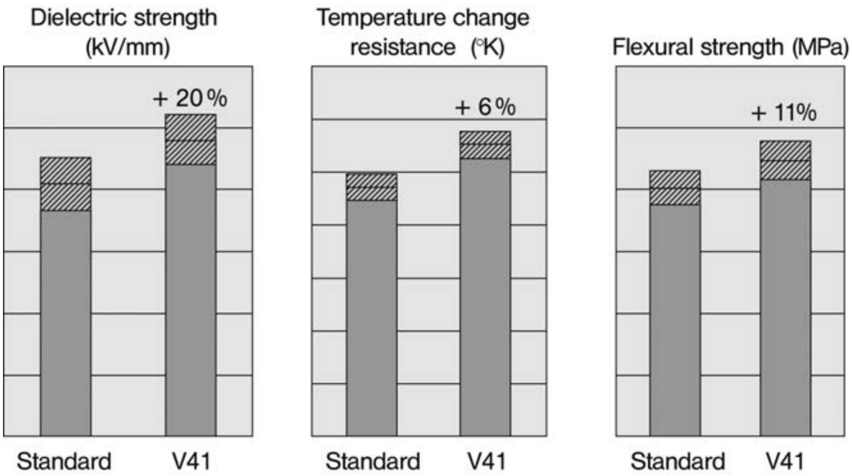

Figure 3: Improvement of ceramic properties based on modified additives

higher voltages will be required. The contradictory demands – thinner walls on the insulator and higher voltage requirement – necessitate the development of new materials, geometries and methods.

3.1 Importance of the Ceramic

An alumina-based ceramic with an Al_2O_3 (aluminium oxide) content of at least 94 % has established itself as the standard insulator material for passenger car spark plugs, because such a material meets the electrical and mechanical demands in terms of dielectric strength even at high temperatures (up to 1,000 °C). Moreover, high levels of raw material availability and process safety ensure an optimum cost/benefit ratio.

To produce the ceramic, minerals such as kaolin, soapstone and dolomite are added to the Al_2O_3. They deliver the oxides (SiO_2, CaO and MgO) required for the sintering process and also enhance the rheological properties of the spray slip and the plastic properties of the pellets required for the pressing and grinding process.

Alongside the morphology of the Al_2O_3 crystallites, the oxides used determine the dielectric and mechanical properties of the insulator, especially at high temperatures. The factor considered to be key in determining the material properties of the ceramic currently employed, however, is the residual porosity, caused by pellets which have not been destroyed by pressing. Pores with diameters of as much as 50 μm result in some cases.

3.2 Improvement of Ceramic Properties

In order to substantially reduce the residual porosity and so improve dielectric and mechanical strength, modifications to the additive materials were investigated. To this end, wax suspensions were added to the slip prior to spray drying. They influence the adhesion of the primary pellet particles and the drying process during spraying, and assist compaction during molding. The reduction in residual porosity achieved in this way is presented in **Figure 2**. The improvements in properties achieved with this ceramic (designated V41) are presented in **Figure 3**. The plan is to manufacture M12 spark plugs with a voltage requirement of > 40 kV from this modified ceramic in future.

The use of Al_2O_3 also offers further potential for improvement based on a reduction of the sinter additives, the use of raw materials with smaller grain sizes, and on process modifications, enabling dielectric strengths of > 30 kV/mm to be achieved.

3.3 Spark Plug Design Modifications

For spark plugs with M12 threads the standard allows three different dimensions:
- M12 x 1.25 with Hex 16 mm and insulator neck 10.5 mm (ISO 2705)
- M12 x 1.25 with Hex 14 mm and insulator neck 9.0 mm (ISO 16 246)
- M12 x 1.25 with Bi-hex 14 mm and insulator neck 10.5 mm (ISO 22 977).

In these dimensions, the gas pressure tightness of the spark plug must be safely attained at the specified tightening torque. The development goal was to shape the metallic spark plug body so that the required tightness is safely attained at the maximum tightening torque of 25 Nm. **Figure 4** presents the gas pressure tightness of the spark plug as a function of the tightening torque. In conformance to the gas pressure tightness, the measurable deformation of the thread begins at 40 Nm, **Figure 5**.

4 Service Life Requirement

The required service life of M12 spark plugs is 60,000 to 100,000 km – the same as for the M14. The increase in voltage requirement due to wear of the spark plug spark gap needs to be minimized in order to achieve such durability, and that necessitated the development of new electrode geometries, materials and methods.

4.1 Wear of Low-cost Spark Plugs

The wearing mechanism on nickel alloys, **Figure 6**, is essentially dictated by oxidation, because the oxide layer which forms penetrates through to the base material due to the spark discharge and is destroyed in the process. The thicker the oxide layer, the deeper are the craters, and the greater is the material loss. As a result, nickel alloys with a thinner, permanent oxide layer are required. **Figure 7** presents the influence of different alloying additives on the wear index determined during engine running.

4.2 Wear Reduction on High-end Spark Plugs

The wear of spark plugs featuring electrodes clad in oxidation-stabilized noble metal is fundamentally lower. A permanent join of the noble metal to the nickel-based spark plug electrodes is essential though. The key factor in attaining this is to counteract the thermomechanical stresses occurring due to differing coefficients thermal expansion in the weld zone. This is done – **Figure 8** (A) based on the example of a ground electrode – by laser welding, forming an additional alloy zone in the border area of the noble metal cladding.

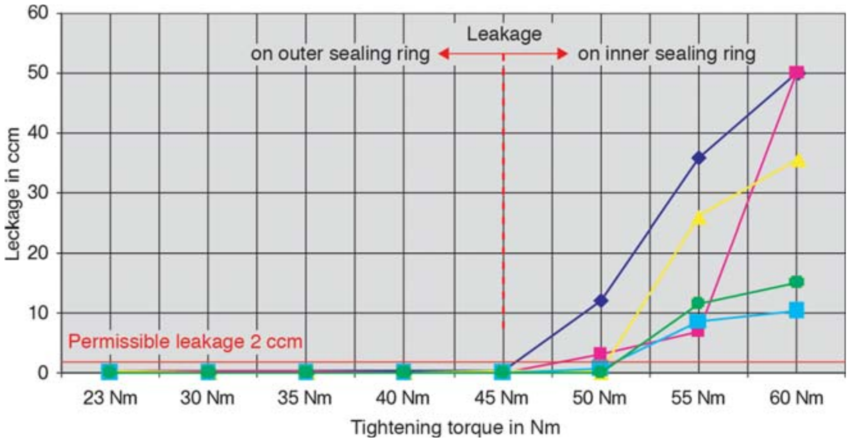

Figure 4: Spread of leakage quantity of an M12 spark plug as a function of tightening torque

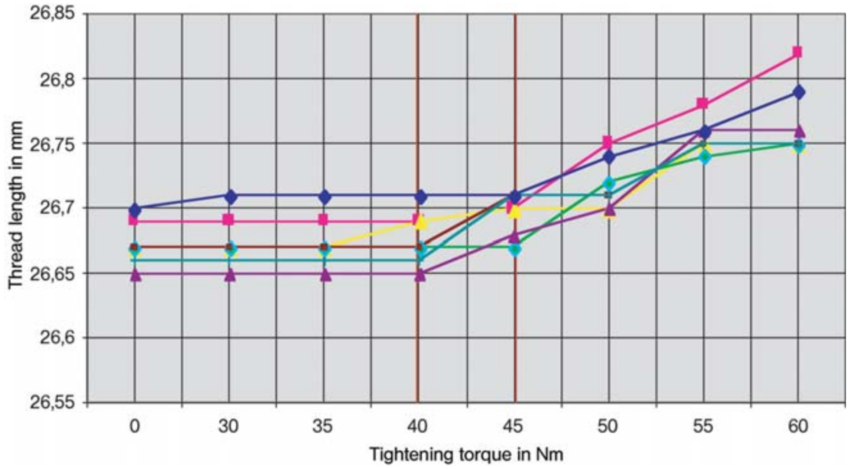

Figure 5: Spread of thread elongation of an M12 spark plug as a function of tightening torque

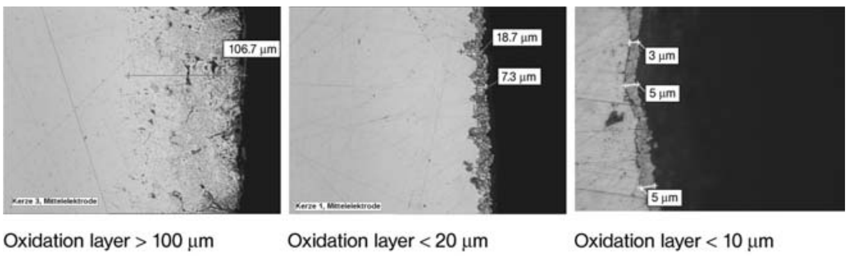

Figure 6: Influence of the nickel alloy on the formation of the oxide layer in engine running

5 Manufacture of High-end Spark Plugs

A further key requirement for reliable sparking of gasoline engines featuring jet-guided direct injection is a more precisely manufactured spark plug with a positionable ground electrode. This demands defined spark gap flow control in the combustion chamber as well as narrower injector/spark plug matching tolerances, with a tight spark location tolerance.

5.1 Noble Metal Spark Plugs with High Coverage

Spark plugs for high mileages are usually designed with a noble metal cladding on the center and ground electrodes. A key factor determining the service life durability of the spark plug is the coverage of the noble metals, **Figure 8** (B). BERU has developed a method which ensures at least 92 % coverage of the noble metal surfaces. This permits a reduction in noble metal usage.

5.2 Reduction of Manufacturing Tolerance

Adding together all the tolerances, conventional spark plugs achieve an accuracy of spark gap positioning in the combustion chamber of up to 1.7 mm. Consequently, they are not suitable to meet the needs described, as misfiring may occur [6].

By optimizing the manufacturing processes and applying different thicknesses of the inner gasket, the sparking position tolerances have been narrowed to such an extent that the position of the spark gap is safeguarded to an accuracy of maximum ± 0.2 mm, **Figure 9**.

5.3 Position-oriented Ground Electrode

Just as important as precise spark location positioning is a defined alignment of the ground electrode, so that the mixture formation is not hindered. This precise positioning of the ground electrode likewise demands a defined thread face in the cylinder head.

The shape and position of the thread profile are used as a reference for precisely positioned welding of the ground electrode. In this, the body is piloted on the outer sealing seat and with a turning movement the body's thread profile is set to the desired position within a measurement window. By aligning, adjusting and positioning the body using an optical measurement system, a tolerance of ± 15° is attained, **Figure 9**.

6 Measurement System

The development of an engine-specific spark plug demands close collaboration between the vehicles and spark plug ma-

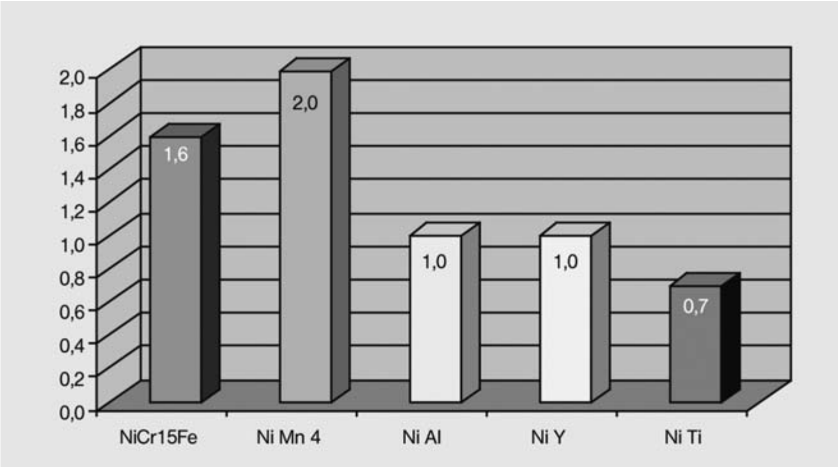

Figure 7: Influence of the nickel alloy on relative wear in engine running

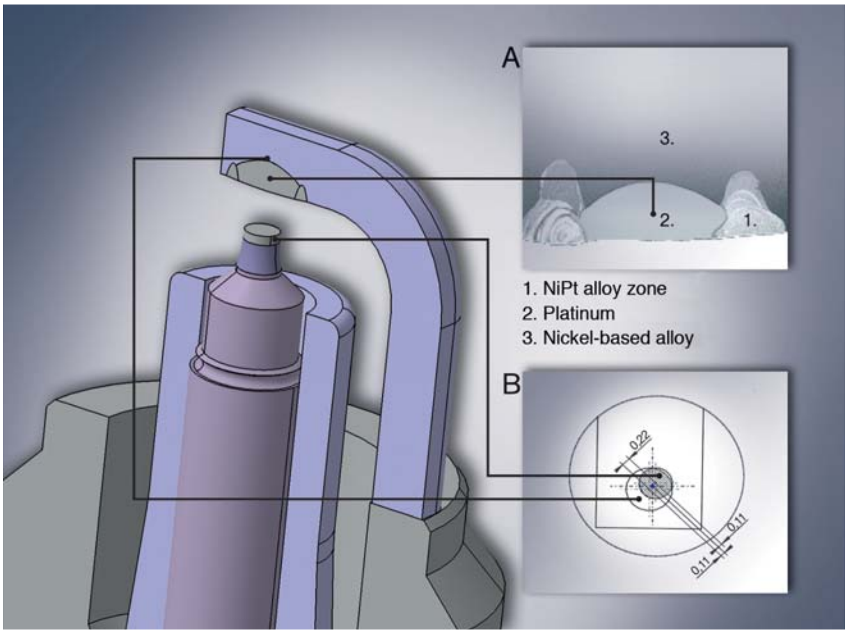

Figure 8: Formation of the alloy zone in the border area of the noble metal cladding in laser welding (A); minimum 92 % coverage of the noble metal surfaces based on optimized manufacturing process (B)

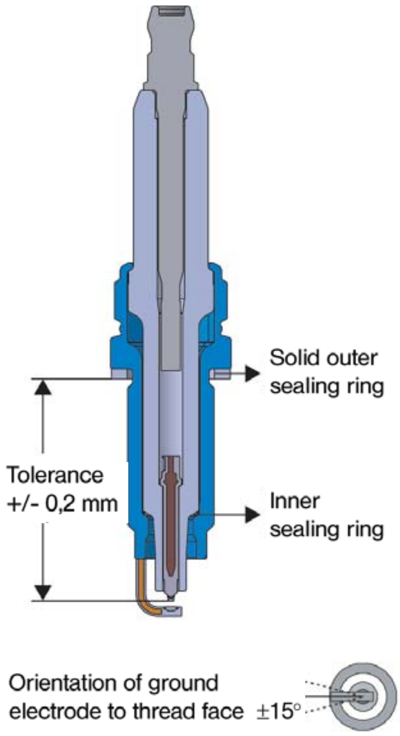

Figure 9: M12 spark plug with positioned ground electrode and precise spark location

nufacturers. The requirements involved in achieving this include facilities for determining

- the appropriate thermal value of the spark plug
- the electrode temperatures
- the ignition voltage requirement
- the ignition voltage supply.

It is also necessary to test the cold starting behavior of the spark plug. This special measuring system was developed by BERU, and is available as a mobile application unit.

6.1 Thermal Value

The thermal value (TV) is an indicator of the thermal withstand capability of the spark plug. It is a function of the ratio of the absorbed heat to the discharged heat. It is determined on the basis of comparative measurements against a reference. The aim of thermal measures in the design of a spark plug is to achieve the best compromise between good cold starting performance and adequate safety prior to preignition in the engine, taking into account the electrode temperatures.

The facility to record the preignition and postignition behavior by means of ionic current measurement enables precise definition of the thermal value.

6.2 Electrode Temperature

Measuring the temperature of the center and ground electrodes safeguards service life durability, as electrode burn-off increases drastically as the temperature rises. In mobile operation, spark plugs are prefitted with thermocouples for the purpose. For stationary comparative measurement, a special engine with an optical access for pyrometric measurement is available, **Figure 10**.

6.3 Ignition Voltage Requirement

The electrode gap (EG) of the spark plugs must be selected such that safe mixture ignition (large EG) with an adequate ignition voltage reserve (small EG) is ensured even at the end of the spark plugs' service life. Measurement of the ignition voltage requirement and supply is used to check the ignition voltage reserve. These measurements are most usefully performed in the vehicle, with spark plugs which have reached the end of their service lives, as this is the best way to represent the dynamic driving states critical to the ignition voltage requirement.

The BERU mobile measurement system permits selective measurement of the ignition voltage requirement and supply at up to eight cylinders simultaneously. The system determines the high voltage values over time, as well as the envelopes of minimum and maximum values. It also provides information on the frequency distri-

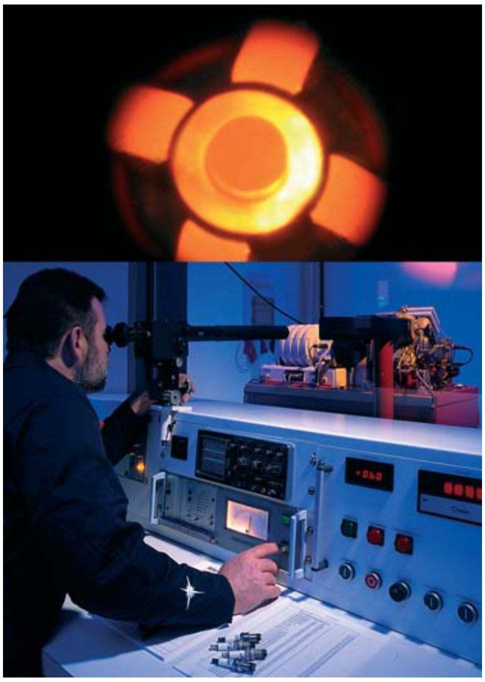

Figure 10: Pyrometric temperature measurement in a special engine with optical access on a four-pole surface-gap spark plug

Figure 11: The new BERU cold cell with two-axle roller dynamometer

butions of the individual high voltage classes.

6.4 Cold Start Test

The cold start characteristics of the spark plugs are checked following a defined test cycle in the vehicle on the roller dynamometer. The cycle is run at ambient temperatures and coolant temperatures down to -20 °C, and comprises multiple starts followed by driving under low engine load.

Assessment criteria are the number of possible starts and/or the characteristic of the shunt – that is, the short to ground due to fuel or soot deposits on the insulator nose resulting from incomplete combustion.

7 Technical Test Requirements

To perform the above test, a cold cell with a roller dynamometer is required, as is available at the BERU R&D center, **Figure 11**. Key features:

Cold cell

- Entry height: 3.50 meters. Length: 14 meters. Width: 5.50 meters.
- Temperature range: -40 °C to +30 °C

Roller dynamometer

- Model: Two-axle roller dynamometer with 48 inch roller diameter
- Rated power output: 195 kW per axle (continuous running)
- Vmax: 250 km/h
- Track width: 914 mm to 2,743 mm
- Wheelbase: 2,100 mm to 4,700 mm
- Axle load: 3.5 tones per axle

8 Summary and Outlook

The effects of changing gasoline engine combustion systems were presented based on the example of an M12 spark plug.

The small design requires optimization of the ceramic insulator and the mechanical construction. Precise spark locations and positioned ground electrodes can be attained by improved processes and new manufacturing methods. High service life expectations are met by high-end noble metal concepts. Other requirements include appropriate application tools and experience, in order to achieve an optimum design of the spark plug within a short space of time.

The trend outlined at the beginning will be sustained: increasing charge levels, higher specific power outputs and ever tighter space inside the cylinder head mean spark plugs will become even smaller. The first project – an M10 spark plug – has already been launched, posing a challenge to BERU‘s engineers.

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BERU Aktiengesellschaft
Mörikestrasse 155,
D-71636 Ludwigsburg
Postfach 229,
D-71602 Ludwigsburg
Telefon: ++49/7141/132-693
Telefax: ++49/7141/132-220
info@beru.de
www.beru.com