

# High Accuracy Glow Plug-Integrated Cylinder Pressure Sensor for Closed Loop Engine Control

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## ABSTRACT

The PressureSense Glow Plug combines a miniature cylinder pressure sensor with the automotive glow plug. The 1.7mm diameter fiber optic-based sensor is welded into the glow plug heater and the signal conditioner is encapsulated into a "smart connector" located on the top of the glow plug body. The sensor offers accuracy better than  $\pm 2\%$  of reading between 220 bar and 5 bar and  $\pm 0.2$  to  $\pm 0.5$  bar error for pressures below 5 bar. The performance of "dummy" as well as glowing and pressure sensing devices was evaluated on various engines and over a wide range of engine operating conditions.

## INTRODUCTION

Cylinder pressure is the fundamental engine parameter that provides the most direct and valuable information for advanced control and monitoring systems of internal combustion engines [1]. Such systems are presently developed by numerous engine manufacturers in order to meet the emission regulations that currently affect with a varying degree of severity all types of engines including those used in passenger cars, trucks, off-road vehicles, watercrafts, ships, and locomotives as well as stationary engines used in gas and oil pipelines or electricity generation.

Diesel engines in particular can significantly benefit from cylinder pressure-based controls resulting in reduced harmful emissions, lower engine noise levels, better fuel economy, and drivability. Recently, 15% and 12% reduction in soot and NO<sub>x</sub> emissions, respectively, were demonstrated through closed loop control of fuel injection based on information provided by pressure sensors located in all [2] or one cylinder [3]. Other benefits of a cylinder pressure-based closed loop combustion control include: stability over lifetime (tolerances, emissions), other sensors can be simplified or even eliminated, reduction application effort (simplified engine maps), enabling highest power-density, OBD, compensation for fuel quality, torque feedback and control, improved cold-starting and engine warm-up, and enabling new combustion concepts such

as Homogenous Charge Compression Ignition or Premixed Charge Compression Ignition [4]-[5].

In diesel passenger cars and light duty trucks a preferred way of introducing a cylinder pressure sensor into a combustion chamber is through a glow plug so no engine head modifications are required. During the recent few years a number of different concepts of glow plugs with pressure measuring capability has been proposed, including designs based on piezoelectric washers mounted in various glow plug places [6]-[8] or a glow plug heater acting as a transfer pin in conjunction with a piezoresistive transducer [9]. It is to be noted, however, that all these devices, which in effect measure cylinder pressure "indirectly", share some significant performance and durability-reliability drawbacks due such factors as valve and injection actuation, engine vibrations, glow plug torque effect, engine head temperature changes, vibration damage and wear of moving device components, and glow plug heater operation. In contrast, the fiber optic-based design described here relies on an accurate and durable "contact-less" principle where cylinder pressure acts on a sensor diaphragm that does not contact the optical fibers. In addition, the package relies on the sensing element welded into a glow plug heater without any moving or preloaded components minimizing all major engine artifacts, as described below. As a result, the sensor offers high accuracy at all crank angles, all engine operating conditions, and at low pressures, allowing the most advanced closed loop control strategies.

## DEVICE DESCRIPTION

The PressureSense Glow Plug<sup>TM</sup> (PSGP) combines a miniature, high temperature cylinder pressure sensor and a glow plug used in passenger car diesel engines. Figs. 1, 2 and 3 show the PSGP designs targeted for production engines based on glow plugs with either metal sheath or ceramic heaters. The 1.7mm diameter fiber optic-based sensor is welded into the heater having a pressure passage to guide combustion gasses to the sensor diaphragm. Due to the location of the pressure orifices in the vicinity of the heating coil the device "self-cleans" during glow plug activation and engine full load

operation, when the front of the pressure passage reaches temperatures above 650°C. In order to minimize the standing wave resonance effect due to the passage, the length of the axial pressure passage is not longer than 5mm. Furthermore, by having the passage diameter equal to that of the sensor the Helmholtz resonance is eliminated. It is to be noted that in the design shown the high electrical current is conducted through the sensor body to the glow plug heating coil during glow plug operation, which is uniquely possible with a non-electric sensor only. Finally, the optoelectronic signal conditioner is encapsulated into a connector directly attached to the glow plug body with three smaller sensor pins and the fourth (largest) pin dedicated to the glow plug heater, as shown in Fig. 1.

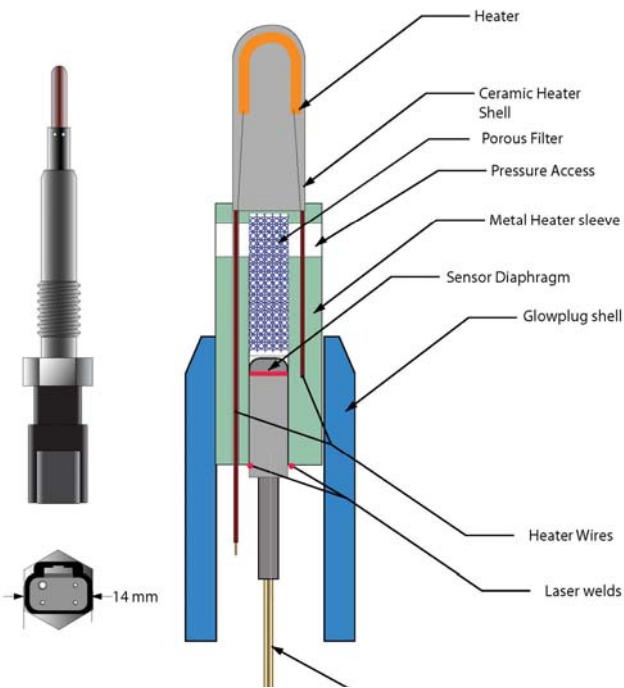


Fig. 1. PSGP based on ceramic heater



Fig. 2. PSGP based on metal sheath heater

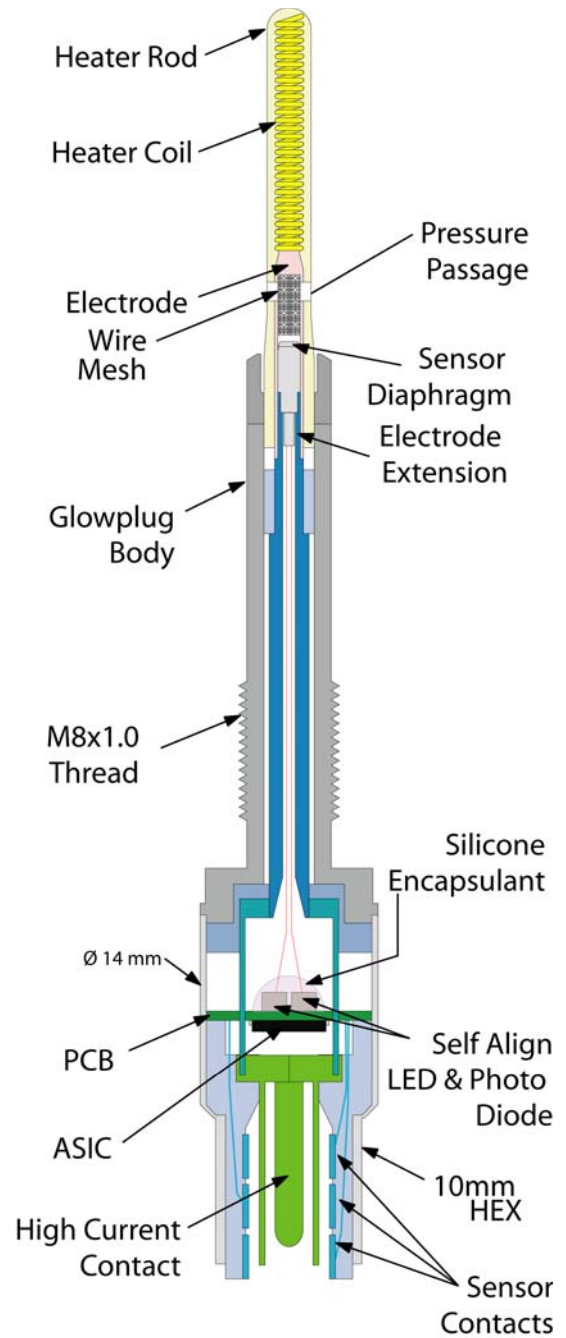


Fig. 3. Details of PSGP construction based on metal sheath heater

In an alternative design shown in Figs. 2 and 3, the connector has a circular shape with the high current pin located concentric with three ring-like contacts for the sensor power, ground, and output voltages.

Since the packages shown in Figs. 1-3 are not yet available, prototype devices have been built with and without glowing function, having the signal conditioner located at the end of a 2m-long fiber optical cable. Fig. 4 shows a picture of both sensing and glowing PSGP prototype. As in the design of Fig. 3, the sensor has been welded into a heater pole used in production glow plugs, which has been drilled axially and transversely to accommodate the sensor and the pressure passage.

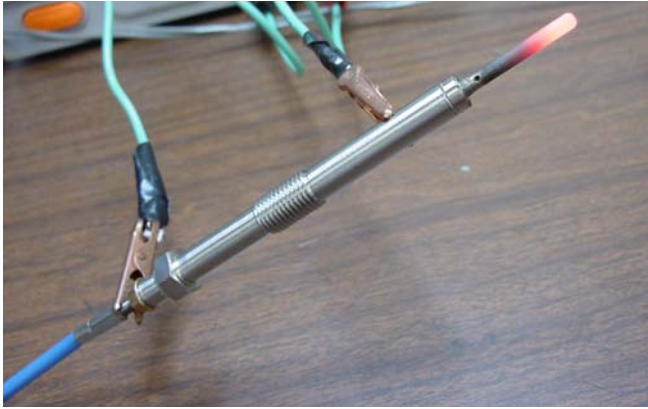


Fig. 4. Prototype fully functional PSGP

The production intent PSGP pressure sensor module shown in Fig. 5 consists of four basic components: sensing head, fiber optic “pigtail”, tube type heater pole with three-prong connection pins, and signal conditioner.



Fig. 5. PSGP sensor module construction

The signal conditioner contains the following parts: LED and photodiode chips, an Application Specific Integrated Circuit (ASIC), and a few discrete electronic components, all mounted on a 12mm diameter board. The large diameter (165micron), illumination-type fibers are permanently bonded to the LED (850nm wavelength, high brightness, 150micron emitting area, point-source type) and photodiode (Silicon) chips. These low cost (encoder type) chips are mounted into miniature SMD packages (0603). For long life reliability the LED is operated at the maximum current of ~10mA.

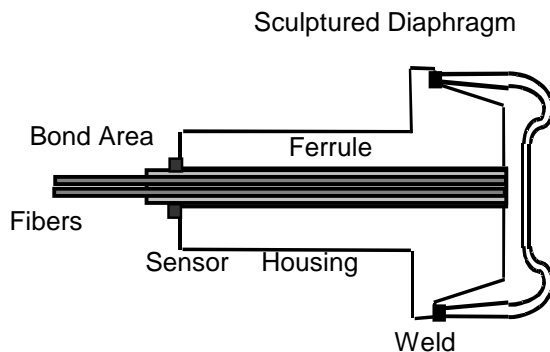


Fig. 6. Sensor head construction

The sensor head, as shown in Fig. 6, contains stainless steel housing with a welded Inconel 718 diaphragm, a Kovar ferrule welded into the housing, and two borosilicate fibers bonded by high temperature solder glass inside the ferrule.

The sensor’s pressure response results from the light intensity change associated with diaphragm displacement [10]. The diaphragm shape and material have been selected to meet the requirement of maximum sensitivity at acceptable non-linearity, low creep, and fatigue life of hundreds of millions of pressure cycles. The sensor is compensated for all major temperature effects encountered in combustion engines: (1) long time-constant effects, of the order of minutes, are associated with varying under-hood engine temperatures ranging from  $-40^{\circ}\text{C}$  to  $150^{\circ}\text{C}$ . Such changes result in changing the LED output, which if not compensated for will lead to errors as large as tens of percent. In addition, the LED output degrades at elevated temperatures. (2) Medium time-constant effects, of the order of a few seconds, are associated with increased diaphragm deflection during increased engine load (due to increase in diaphragm temperature). (3) Short time-constant effects, of the order of several milliseconds, are associated with diaphragm distortion due to exposure to combustion gasses.

The long-term errors, both in the signal conditioner and the sensor tip areas, are compensated by the Auto-Reference technique [11]. The associated circuitry regulates the LED light intensity in such a way that the minimum sensor output voltage (offset) is maintained at a constant level throughout the sensor life, resulting in offset drift-free sensor operation. In a reliable design the mid-term thermal error compensation is done without use of any temperature measuring devices but instead relies on the auto-referencing circuitry and an optimum selection of sensors components’ thermal expansion coefficients and dimensions: Through intentional increase in the distance between the diaphragm and the fibers with increasing sensor temperature, the resulting reduction in sensor electronic gain compensates for the diaphragm’s deflection increase with temperature[11], up to  $400^{\circ}\text{C}$ . Finally, the short time constant error is minimal due small heat flux associated with the diaphragm’s 1.7mm diameter, the small diameter of the pressure passages, a wire mesh filter acting as a heat exchanger as well as a particulate trap, and the low average sensor temperature resulting from the sensor location close to the glow plug sealing surface.

## SPECIFICATIONS, PERFORMANCE, AND DURABILITY

The PSGP targets engine control and monitoring applications that require high accuracy pressure detection at all crank angles, under all operating conditions, and in particular at low pressures. Basic device specifications are summarized in Table 1.

Table 1. PSGP specifications

Pressure range:	0 - 220 bar
Over-pressure range:	Minimum 1.5x pressure range
Accuracy (under all operating conditions)	+/-2% of reading above 5bar
Accuracy (under all operating conditions)	+/-0.2 to +/-0.5 bar below 5bar
Frequency response:	0.5-1Hz to 10-20 kHz
Temperature Coefficient of Sensitivity	< 0.01%/°C
Sensor diameter:	1.7 mm (1mm possible)
Signal to Noise Ratio	1000:1(@ 20 kHz)
Sensor housing continuous temperature:	-40°C to 400°C
Connector temperature range:	-40°C to 150°C
Sensor Output:	0.5(0.3)V - 4.5 (3.5)V
Power supply	5V, 20mA max current
Life time:	10k hours or 500 Million cycles
Glow plug type/thread	Metal sheath or ceramic/M8 to M14

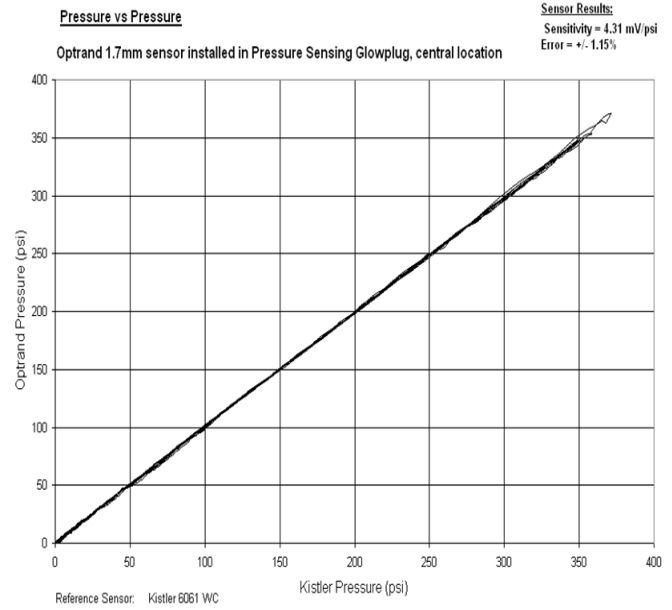


Fig. 7b. Pressure vs. pressure comparison

Figs. 7a and 7b demonstrate typical performance of the prototype device as tested on a single cylinder genset gasoline engine. The water-cooled Kistler 6061 piezoelectric transducer was used as reference. As seen in Figs. 7a and 7b the sensor demonstrates excellent linearity, no hysteresis, and a minimum thermal shock error. It is to be noted that the pressure response shows some small “ringing” effect due to the PSGP pressure passages. However, this ringing can be easily filtered as the characteristics frequencies of interest in diesel engines are below the ringing frequency.

Figs. 8 and 9 show the comparisons between the Indicated Mean Effective Pressure and 50% mass fraction burn values calculated based on the outputs of four “dummy” PSGPs (non-glowing) versus the values obtained with Kistler 6053 transducers mounted in the same cylinders [12]. The sensors were installed in a 4-cylinder 1.9l common rail passenger diesel engine, which was operated in a test cell under all engine RPM and load conditions. The accuracy of the calculated values obtained under the most demanding partial load conditions shown in Figs. 8 and 9 is within 1.5% of the values obtained with the reference transducer. As reported by the testing organization, Optrand devices demonstrated drift free operation, which was not the case for the competing products.

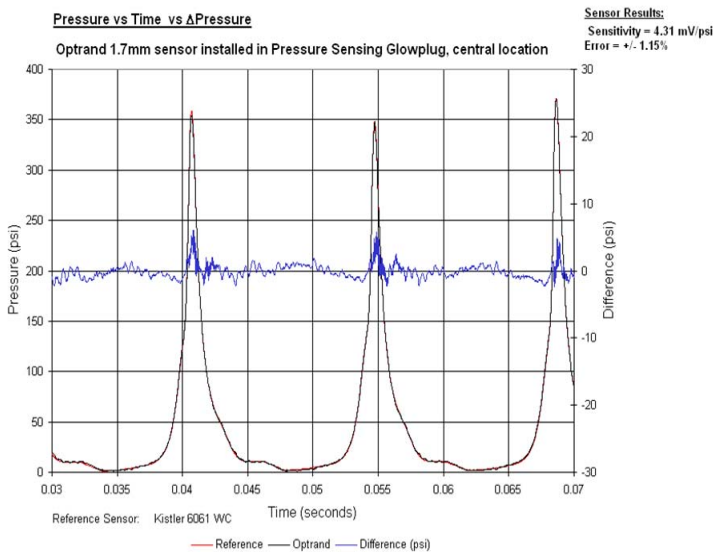


Fig.7a.Pressure vs. time performance comparison

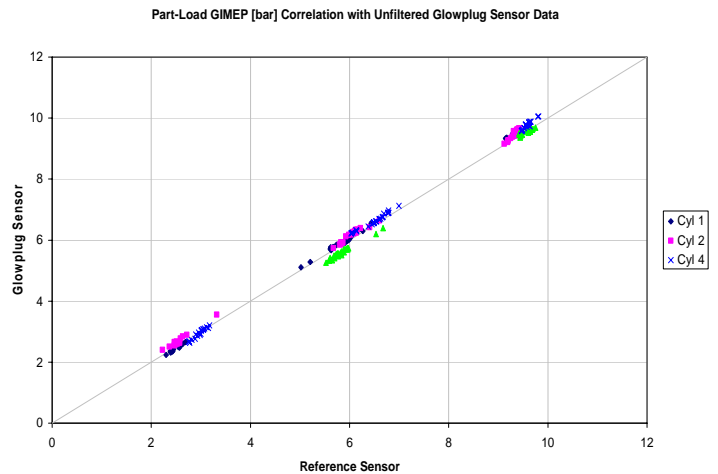


Fig. 8. IMEP comparison between “dummy” PSGP and reference transducer

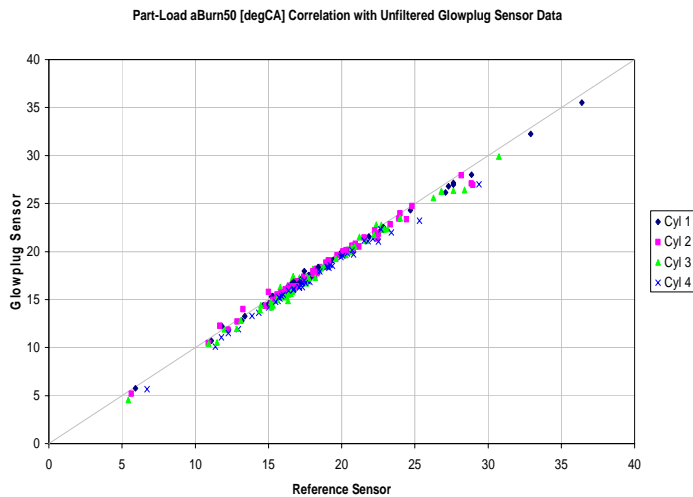


Fig. 9. 50% mass fraction burned comparison between “dummy” PSGP and reference transducer

For the last 7 years the same 1.7mm diameter sensor as utilized in the PSGP has been employed in various packages and engine applications. In the longest to-date continuous application the gas injector-mounted sensor has been operated approximately 18 thousand hours over 3 years in natural gas large bore gas engines. During the last 5 years several hundreds of non-glowing PSGPs have been used by several engine manufacturers in various engine durability test-cell and road tests as well as the development of closed loop control strategies. In the longest durability tests so far tens of non-glowing PSGPs have been used over 800 hours each without any performance degradation or soot fouling. The durability tests of the glowing PSGP prototypes are ongoing.

## CONCLUSION

The PressureSense glow plug combines the 1.7mm diameter cylinder pressure sensor and a glow plug in one, higher functionality device. The dual fiber-based dynamic sensor utilizes the proven principle of reflected light intensity changes due to a flexing metal diaphragm. The sensor's miniature signal conditioner contains a Si photodiode, a near infrared point-source LED, and an associated ASIC encapsulated in a 4-pin automotive-like connector. The auto-referencing circuitry maintains sensor calibration and drift-free operation by compensating for the signal conditioner aging and temperature effects over a range of  $-40^{\circ}$  to  $+150^{\circ}\text{C}$ . In a reliable and durable design the sensor head materials and dimensions are optimized to compensate for engine load related errors, without the use of any temperature probes, resulting in the thermal coefficient of sensitivity of  $\pm 0.01\%/^{\circ}\text{C}$  over the sensor tip temperature range of  $-40^{\circ}$  to  $+400^{\circ}\text{C}$ . The glow plug integrated sensor offers the total accuracy of better than  $\pm 2\%$  against a water cooled reference transducer at pressures above 5 bars and less than  $\pm 0.2$  to  $\pm 0.5$  bar error (depending on the package and application) for pressures below 5 bars.

In the longest to date continuous application the same 1.7mm sensor as used in the PSGP has been operated approximately 18 thousand hours over 3 years in natural as large bore gas engines. In the longest diesel vehicle tests tens of non-glowing PSGPs have been used over 800 hours without any performance degradation or soot fouling.

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