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13. ABSTRACT (Maximum 200 words)
The FED-SAVER program refined and continued the development of an in-cylinder, high temperature pressure sensor by demonstrating that it can be successfully inserted into diesel engines for routine feedback control of each individual cylinder. There were two major goals for this program. Successfully accomplished, these showed that the sensors can be developed into an engine monitoring and control device with potential to significantly reduce emissions and improve fuel efficiency. The first goal was to revise and refine the MEMS sensing element die. The second goal was the implementation of the second generation packaging concept (Gen 2). The revised package will enable easy integration of the sensor into the engine. Sensors were tested both under simulated and diesel engine conditions.

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Acronyms

HC	Hydrocarbons
CAD	Computer Aided Design
DOT	Department of Transportation
EPA	Environmental Protection Agency
FED-SAVER	Advanced Vehicle Emission Reduction Sensor
FEA	Finite Element Analysis
FEM	Finite Element Method
FEMLab	COMSOL Multiphysics® w/MEMS Module
FTA	Federal Transit Administration
l	length in mm.
MEMS	MicroElectroMechanical Systems
NOx	Nitrogen Oxides
PM	Particulate Matter
psi	Pounds per square inch
ρ	Resistivity in Ohms·mm/mm^2
t	thickness in mm.
SBIR	Small Business Innovative Research
w	width in mm.

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1. Executive Summary

Health and environmental problems caused by smog (ground-level ozone) and particulate matter (PM) are significant problems in many regions of the United States that can be partially attributed to diesel engine emissions. Diesel engine emissions which are, or may be, harmful to people include fine PM, carbon monoxide, sulfur oxides, nitrogen oxides, volatile hydrocarbons and other compounds which are suspected or known to cause cancer, respiratory disease, or other common but serious ailments in humans[1]. As a result Congress established a comprehensive approach to significantly reduce the hazardous output of these engines. The EPA has worked to reduce emissions for a variety of motor vehicle classifications through cleaner fuels, cleaner burning engines etc. To date, these measures have not significantly improved[2] the health and environmental problems associated with pollutants from diesel engines. Thus, the transportation industry is seeking alternative, affordable, solutions that will allow motor vehicles including diesel powered vehicles to meet more stringent emission standards.

Orbital Research's Fuel Efficient Diesel Engine Sensor for Advanced Vehicle Emission Reduction (FED-SAVER) program has been focused on the development, test and validation of an innovative low cost pressure sensor that will enable lower emissions through better control of the engine (engine management). Many researchers have shown that significant emission reduction could be achieved through managing the combustion process if an affordable sensor existed. This program addresses this industry wide need by demonstrating a sensor that can operate in harsh engine environments of both high temperature and high pressures.

Current state-of-the-art engine management systems treat the entire engine as a "black box," applying the same combustion management to each cylinder regardless of the cylinders' individual performance. This approach is used due to a lack of effective and affordable in-cylinder combustion sensors: cylinder by cylinder combustion management is known to reduce emissions (and conserve fuel). Current engine management technology uses sensors placed immediately before the engine and immediately after the engine because affordable harsh environment sensors capable of surviving in an engine cylinder do not exist. Consequently, engine management is currently based on estimated combustion conditions inside the engine, estimated according to what went in (manifold pressure and temperature sensors) and what came out (oxygen sensors and other emission sensors) of the engine. Thus, current engine control technology has significant potential for error in fuel delivery, resulting in increased toxic emissions. Specifically, when a single cylinder is running sub-optimally, the entire engine is adjusted as a whole, thus resulting in a sub-optimal trade-off among various emissions and fuel economy.

The Orbital Research sensor that was further developed in this program will enable real-time engine combustion control **on a cylinder-by-cylinder basis.** These harsh environment sensors will provide feedback to on-board computers (electronic control unit) to efficiently and cost-effectively reduce emissions and improve fuel efficiency of all types of motor vehicle engines.

Orbital Research has extensive experience in microfabrication and sensor technologies that have been important skills to complete this effort. This experience has enabled the refinement of

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1 California Environmental Protection Agency, Air Resources Board and Office of Environmental Health Hazard Assessment, Proposed Identification of Diesel Exhaust as a Toxic Air Contaminant, April 1998 http://www.arb.ca.gov/toxics/dieseltac/finexsum.pdf

2 US EPA, Air Quality Planning & Standards, The Plain English Guide to the Clean Air Act – Mobile Sources, http://www.epa.gov/oar/oaqps/peg_caa/pegcaa04.html

an existing prototype motor vehicle sensor that has been demonstrated in laboratory diesel engines. The low-cost and high performance of the proposed sensors may ensure implementation by diesel engine manufacturers, maintenance companies and end-users.

Current state of the art sensors range in price from $900 to $3,000: unaffordable for insertion in each cylinder of a diesel engine. Orbital Research's proposed sensor has a target price of $20 to $50 for automotive and heavy duty over-the road diesel engines, respectively.

2. Project Description and Background

Orbital Research continued the development of an innovative combustion pressure sensor targeted to dramatically reduced emissions of nitrogen oxides (NOx) and particulates from diesel engines, and is expected to do so ***without a fuel economy penalty.*** Fuel savings may even be achieved. Controlling combustion based on measured in-cylinder pressure is the acknowledged gold standard for cylinder-by-cylinder engine control to improve fuel economy (approximately 3%) and reduced emissions.[3,4] To date, adoption of a combustion pressure based engine control system has been thwarted by the lack of a low cost sensor.

The sensor being developed is based on shape memory alloy technology, fabricated using Microelectromechanical systems (MEMS) processing techniques.[5] The key to the technology is the anticipated simplicity of both the unique materials technology and of its fabrication. The simplicity should result in a cost/price point that conventional pressure sensor technologies cannot approach. This will allow high temperature, pressure sensors to be economically installed in each cylinder of every diesel engine (and eventually every internal combustion engine). This will allow an unprecedented level of control over each individual combustion event, essentially a continuous tune-up for the engine, achieving optimal power from each stroke for best fuel economy and optimal temperature profiles to minimize the emissions.

The sensor itself takes advantage of the phase change behavior of shape memory alloy material. By straining the element (through applied pressure on a diaphragm) a metallurgical phase transformation occurs. The child phase, which is produced under strain, has a much lower electrical resistivity than the parent phase. This results in a very high signal to noise ratio and thus minimal amplification is required, reducing the cost of support electronics.

The overall goal is to develop a combustion pressure sensor that will allow cylinder-by-cylinder control of diesel combustion in real time. This will allow for much more precise engine control, resulting in dramatic reduction in pollutant emissions without sacrificing fuel economy. Cited studies indicate that an improvement in fuel economy should even be possible. This development work was initially funded by the US Army and National Science Foundation under the SBIR program. Current grants, through EPA and DOT, are intended to further the development of the product towards commercialization. These grants were intended to allow Orbital Research to overcome manufacturing issues that impede implementation in the market place. Successful completion will benefit the nation through reduced pollution and reduced dependence on imported fossil fuels.

To accomplish the goals of this program several key objectives were proposed and specific tasks completed toward this end. The first objectives addressed optimization of design features of the combustion sensor. The next objective was manufacturing of the sensor using a commercial MEMS foundry and packing into an improved housing. Successful completion of these objectives led to testing and demonstration.

3 Amann, C., "Cylinder Pressure Measurement and its Use in Engine Research," SAE Paper 852067, 1985.

4 www.ricardo.com/pages/newsarticle.asp?ID=46

5 U.S. Patent Nos. 6,622,558 B2, 7,258,015 B1 and 7,415,884 B1.

3. Results

The results are presented as related to the originally proposed tasks and the organization parallels the original proposal.

Task 1 Re-Design MEMS Integrated Heater

A key objective of this program was the redesign of a heater to control the temperature of the sensor. Various heater designs and considerations from previous work were integrated into a single, optimal design. The final design consists of traces of platinum, deposited onto a silicon substrate, which was electrically isolated from the sensing element itself, and positioned to ensure that leads can be attached. The details of this design were the elements of this task.

Finite Element Analysis (FEA)

Finite element analysis is a method to estimate how a device or structure will operate using a computer model of the device and a mathematical analysis of it.

A solid model of the sensor including an integrated heating element was created using Solid Edge, computer aided design (CAD) software and analyzed using FEMLab, finite element analysis, software. The goal of this analysis was to determine the power requirements and temperature distribution produced by various candidate designs. A baseline design from previous generation sensors, which did not have an integrated heater was used as the starting point. A platinum heater was added and the geometry, heater thickness, heater width and location on the die were variables.

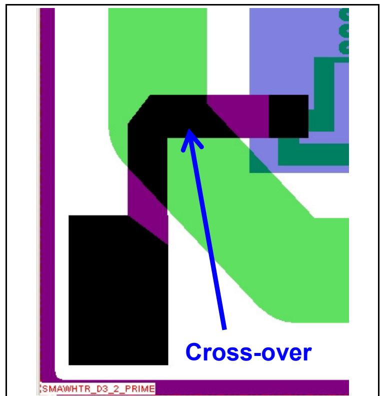

Figure 1: Schematic drawing of the initial MEMS Sensor.

Initial design strategies were shown to have problems in regions where an electrical lead from the sensor would cross-over the heater. (see **Figure 1**) The model showed the possibility of problems where the heater and the sensor crossed. Laboratory testing confirmed this expected problem. Subsequent designs eliminated the lead cross-over points and resulted in a much more uniform and favorable temperature distribution.

The output of the (FEA) model on an intermediate design is shown in **Figure 2.** It indicates that a uniform temperature can be achieved in the most critical portion, of the device (blue-green color). The model also showed that the heater design can quickly reach the required operating temperature.

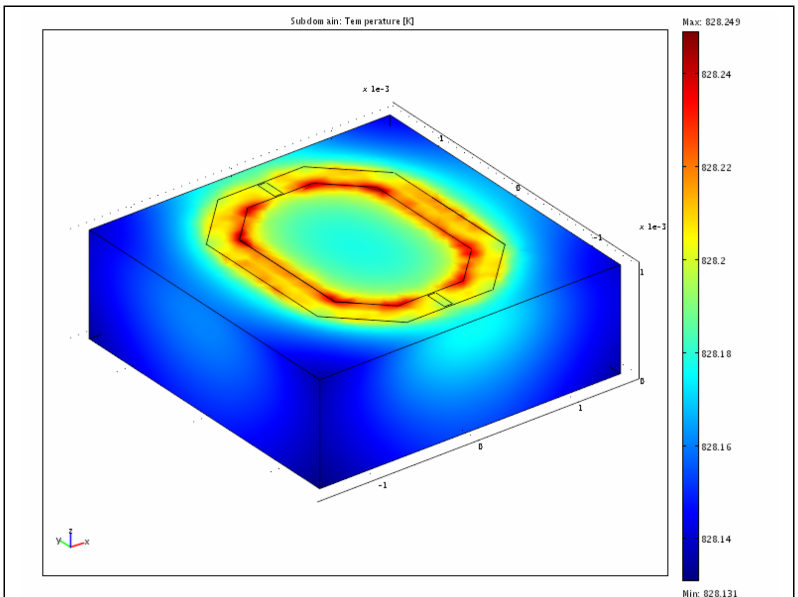

Figure 2. Output of the heater model at steady state.

The final heater design was dramatically improved by using a circular heater thus eliminating the corner points of the previous design. (A close look at Figure 2 shows that these corners result in slight hot spots in the heater.) This design also was facilitated by the development of a circular die after an innovative method was identified for cutting the final sensor shapes. **Figure 3** shows the final heater design, and elimination of the crossover point.

The new design also used a different fabrication method that simplified the overall design. This change made the sensor easier to manufacture and less expensive. It should also be more reliable.

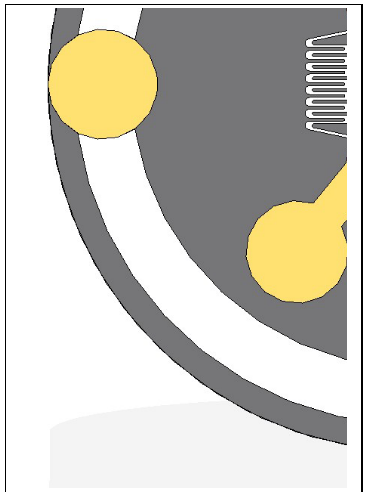

Figure 3: Final MEMS sensor design configuration showing elimination of crossover points.

Lead Placement

The location of the six electrical leads required for operation (two for the heater and four for the sensor) evolved with the heater design since the interactions of the sensor leads and heater were critical. The final placement of the leads on opposite sides of the heater was chosen since it allowed for an overall symmetrical distribution; and FEA analysis showed a more uniform temperature distribution across the die with this configuration. As discussed earlier this design also eliminated the cross-over points among the electrical circuits thus improving reliability and better matching the packaging design plan.

High temperature electrical lead connections were made using a brazing process. A key aspect of the brazing process was the addition of metal bond layers, which is described under Task 3. These “adhesion” layers dramatically improved the bond strength of the lead wires to the sensor and eased the bonding process. Without this, the lead wires don’t always stick. The final layer configuration incorporated lessons learned from previous work from some experiments.

Temperature Control

Four approaches to temperature control using the heater were evaluated during this program. The base-line was a control method previously developed based on a commercial-off-the-shelf sensor-less controller manufactured by Minco Products, Inc. Although this method works, its use with the pressure sensor was problematic since it introduced electrical noise into the sensor signal. To reduce these problems three other methods were proposed. The best method proved to be a custom solution that uses the sensing element bridge resistance for feedback. The design can be operated in two different ways (**Figure 4**). Either mode showed stable temperature control within required tolerances and greatly reduced the electrical noise picked up by the sensor.

Figure 4: Output of temperature controller showing Pulse Width Modulated operation.

Task 2 Re-Design Sensor Element

The sensor elements that have been used prior to this effort were designed based on traditional strain gage design rules. While this was an obvious, and to date effective, place to start, the designs were not optimized for this sensor. In the current program a finite element model was created for the novel sensing materials and designs. The design was laid out using Solid Edge, CAD program and the analysis conducted using FEMLab, just like the heater models.

Design Optimization

To further refine the sensing elements design and establish sensor design rules a Finite Element Model of the sensor element's active materials traces was developed. (**Figure 5**) The key design features of the sensor are shown in **Figure 6** and consist of the various dimensions that make up the sensor. The complete electrical circuit consists of four strain gages in a Wheatstone Bridge electrical configuration. The three dimensional model included the strain gages, insulating layer and silicon diaphragm. In practice, as pressure is applied, the diaphragm is strained at the outer surface thus straining the metal strain gage which results in a change in electrical resistance. Optimization consisted of determining the size and placement of the sensing element trace on the diaphragm that allowed for the strongest signal. This, in practicality, relates to maximizing the active sensor area in the highest strained region of the diaphragm without extending the strain gages into areas that might result in non-linear sensor output. Additionally each application has constraints imposed due to the maximum pressure (plus safety factor) that the sensor will see in use to make sure that the sensor won't break.

In addition to determining the ideal size and location of the strain gages, the model also very accurately calculates the electrical resistance of the bridge based on the geometry, thickness and resistivity of the sensor. The target resistance of the bridge was 350 Ohms. Ideally with a strain-gage based sensor it is desirable to have as high a resistance as practical to minimize power requirements and avoid self heating that would reduce the sensor's accuracy. The resistance (R) of a simple wire or strain gage can be calculated using the materials resistivity (ρ) and wire

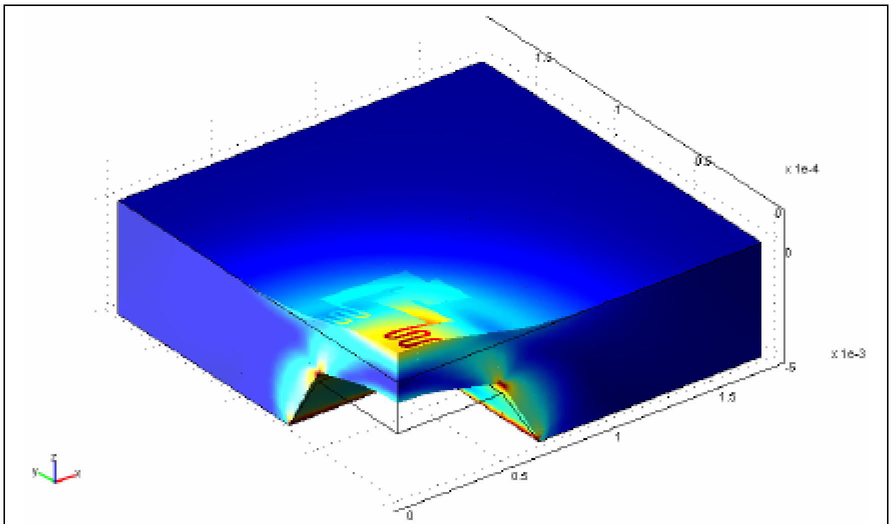

Figure 5. Cross-section model of the sensor element on a diaphragm.

length (l), width (w) and thickness (t) in following equation: $R = \rho \frac{l}{t \times w}$.

Some of the design factors are limited by manufacturing capability. Within those constraints, the dimensions are specified during the MEMS processing sequence. Thickness is kept as low as possible while still allowing for durability and to allow for process variation. Similarly the trace width of the strain gage needs to be a minimized, while still considering the manufacturing capability.

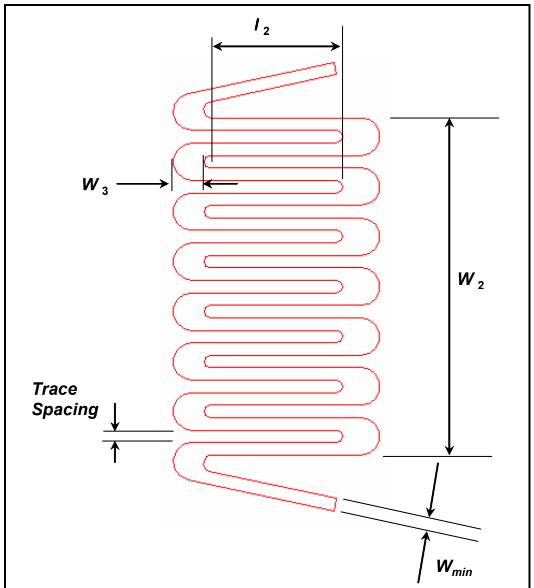

Figure 6: Key design elements of the sensing element trace.

Pad Design

An optimized sensor design is only of value if electrical signals can be applied to it, and an electrical signal received back from it. This means that connections from the electronics to the sensor are vitally important. Orbital Research has mastered a method of connecting wires to the sensor that is capable of surviving high temperature operating environments. Previously the weak link in this system was the connection pads. During the present work experiments were conducted to produce various types of electrical connection pads. From this the best combination of materials was identified for use.

Initial Verification

"Short loop" experiments were completed to test the re-design concepts that were developed. These experiments were part of the risk mitigation strategy, dictating that individual components be evaluated prior to construction of the complete final sensor. Separate MEMS fabrication runs were conducted to test the pad design, a new process for patterning the sensing material, sensor bridge balance and strain gage location. Results from these runs demonstrated preferred design and manufacturing methods.

Task 3 Re-Design Diaphragm

As described above, there are conflicting design requirements for the geometry of the diaphragm. For maximum sensitivity the diaphragm should be as wide and thin as possible. For greatest strength (related to reliability) the diaphragm should be as small and as thick as possible. To minimize the total footprint of the die, and therefore minimize package size, the diaphragm should be small, and the thickness is irrelevant. To complicate this further, the geometry at the root of the diaphragm may significantly affect the diaphragm strength. All of these factors must be taken into account when designing the diaphragms. As reported above, the finite element model that was used to optimize the sensing element which is on top of the diaphragm also includes the same geometric design issues as the diaphragm and therefore was useful again.

Parameterize and Optimize the Diaphragm Model

There are two basic design factors that influence the diaphragm. The first is the width (edge length); the second is the thickness. As described above, there is a trade-off between strength and sensitivity with respect to these two parameters (both of which are highly non-linear). The result is that there are multiple solutions for the diaphragm geometry that will result in adequate strength. The previous model was modified to allow convenient analysis of these parameters. The approach was to set a minimum strength requirement and then determine the solution that allowed maximum sensitivity.

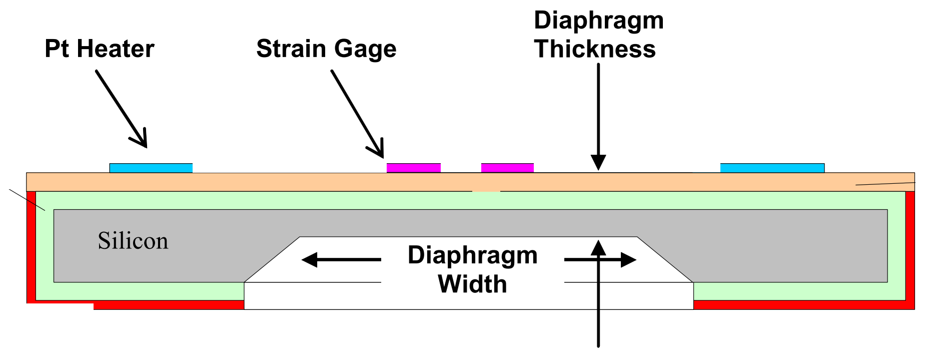

Figure 7: Schematic drawing showing a cross-sectional view of the sensor die and identifying the key parameters. (Not to scale, layers are shown thicker than actual.)

Effect of Singularity at the Root

The etching process used in the MEMS processing of the sensors is exceptionally useful in creating highly reproducible diaphragms in silicon substrates. This is due to the very high selectivity of the etching process in different directions. The downside of this is that it results in an extremely sharp corner where the diaphragm meets the bulk of the substrate. (**Figure 8**) Traditional fracture mechanics suggest that this should cause fracture at very low stresses. Prior to this effort Orbital Research attempted to minimize this problem by adding a second, different type of etch step to round this corner somewhat. Efforts in the present project were made to quantify this effect by using a combination of FEM analysis and experimental verification.

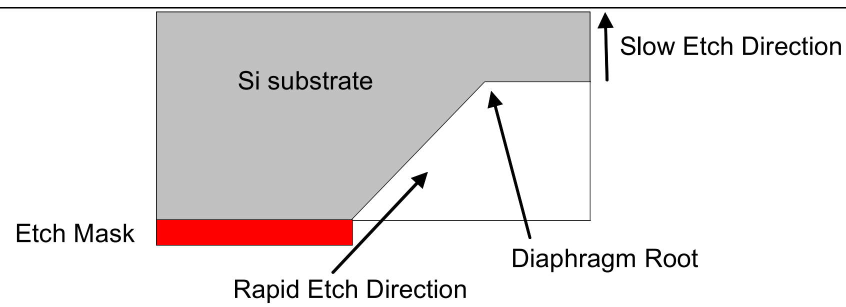

Figure 8: Schematic drawing of Diaphragm etch process showing rapid and slow etch directions of the anisotropic etching process.

The results of the FEM analysis in **Figure 9** show that the addition of a root radius of up to 5 microns substantially decreases the stress concentration and hence stresses in the diaphragm root. This provided the analytical basis/validation for previous empirical decisions. By increasing this to 20 microns an additional 9 to 15% strength could be realized. This results in the ability to design a more sensitive device by using a thinner diaphragm than with the smaller radius.

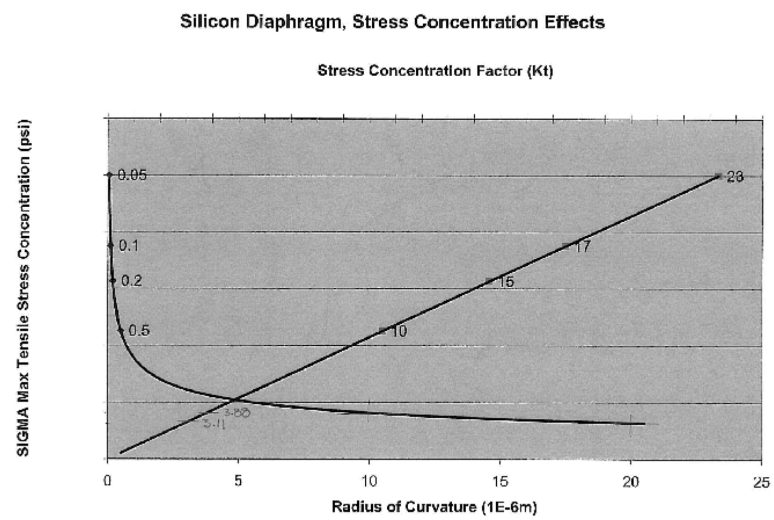

Figure 9: Results of FEM analysis of stress concentration effect at diaphragm root.

To validate the FEM results an experiment was conducted with diaphragm radii of 5 and 20 microns and a control produced with no extra radius. The results are shown in **Figure 10** along with data from previous work. These results show several interesting things. First, the overall strength of the most recent runs show significantly higher fracture pressure than those of past work. The reason for this is unclear but is attributed to differences in MEMS processing capabilities among various vendors. The current program utilized commercial processing sources for wafer processing. In contrast previous efforts were predominantly completed using university facilities and personnel.

With the current wafers the effect of edge radius was most pronounced between the radius and non-radius die. The 20-micron radius dies appeared to show a slight trend toward higher

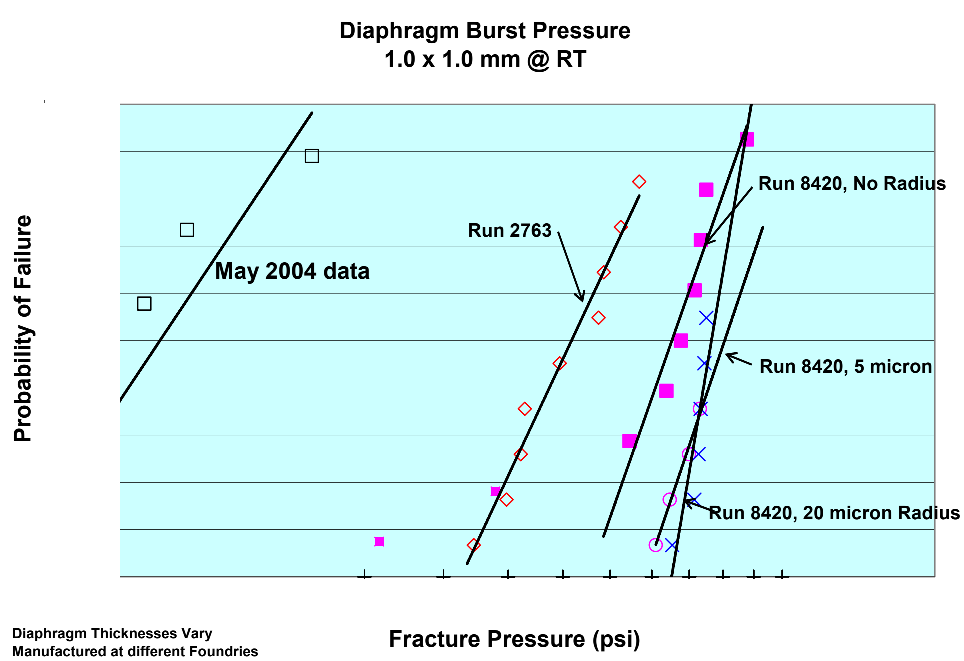

Figure 10: Results of burst testing showing improvements in diaphragm fractures strength due to isotropic etching.

burst pressures, but the differences were not statistically significant. Since this there was no additional cost or down side to the 20-micron edge radius this was used in subsequent processing. As the number of sensors produced increases it is expected that both yield and quality will improve and the improvements showed in the FEA model will most likely be realized.

Final Diaphragm Design

Several design reviews were conducted to review the proposed fabrication plan and make revisions to ensure that the design is the consensus best set of test designs for the diaphragm. Comments from the multi-disciplined engineering and research group were incorporated into a final revised design for the diaphragm. Two different designs were selected for fabrication. One design was conservatively designed for a burst pressure of 3,000 psi and the second for 750 psi which would have higher sensitivity but lower safety margin. This will aid in the ability to customize the diaphragm for other engine applications or for other pressure sensor applications (e.g. turbine engines or refinery process control.)

Test Sample Process Verification and Properties

Experiments were completed as required to test the re-design concepts that were developed. These experiments were part of the risk mitigation strategy, dictating that individual components be evaluated prior to construction of the complete final sensor. The MEMS wafers processed in these runs included only the functionality under evaluation and therefore were less expensive and less time consuming than the complete runs.

Task 4 Fabricate "Optimized" Sense Elements

The results of the three previous tasks were combined into a single fabrication run to verify that the optimization objectives had been met and to provide die for packaging and laboratory and engine performance verification and testing. Because the fabrication runs are relatively expensive and time consuming, a strategy of risk mitigation was adopted wherever feasible. In practice this meant that several designs were fabricated during a single run. The nature of the MEMS production processes is such that this can be accomplished with essentially no additional cost or lead time as compared to processing a single design. The designs selected to be fabricated were chosen according to two basic principles. First, whenever modeling or earlier experimentation had suggested that two or more designs were likely to be functionally similar, both (or all) were fabricated. Second, variations of design parameters about the target values were produced in order to determine the critical design tolerances for future fabrication. A design matrix consisting of four unique placements of the strain gage elements was used and many "copies" of each design were replicated on each wafer. A total of 85 individual sensors were produced on each wafer. Six wafers were produced during the final run.

Detailed Fabrication Plan

MEMS fabrication is a very cost effective method for manufacture of a great number of identical devices. However, the non-recurring engineering costs associated with establishing the process, and the initial low volume runs can be quite costly. Therefore, it is critical that each process step be carefully planned to minimize the likelihood of error during the production process. The detailed fabrication plan was developed based on the results of each of the above tasks. Multiple designs were included as describe to meet the above stated objectives of risk mitigation and design tolerance determination.

Prepare Assembly Drawing of Multi-Functional MEMS Sensor

A thorough graphic description of the final structure, both in plan view and cross-section, was used to help to ensure that there were no unexpected interferences. By creating the plan view drawing in multiple layers it was possible to efficiently create the mask set necessary for production of the sense elements.

Prepare Detailed Process Flow Sheet for Production

The process flow sheet for the sensor production is a detailed description of each of the steps necessary to produce a functional sensor. Without a properly ordered set of production steps, it is easy to accidentally destroy previously fabricated features during the production of subsequent features. The MEMS processing development begins with a high level description that includes the major additive and subtractive steps. Typically, such a process description includes only the layers that remain as part of the finished device.

After the high level description was complete, it was further broken into component parts to ensure that low level details were thoroughly addressed. These details typically include the variety of sacrificial layers necessary during the production process as well as the specific processes necessary to pattern each one.

Prepare Mask Set Drawings

All of the MEMS processes are founded on the use of photo-tools (masks) to accurately and reproducibly pattern the various layers and functional components. Each of these masks is prepared in a CAD package for issue to the mask vendor. (**Figure 11**) The mask designs originated with the solid model described earlier by directly exporting the key plan views of each layer into the CAD package. This ensured optimum performance of the sensor as modeled and compatibility with the process flow to ensure basic functionality.

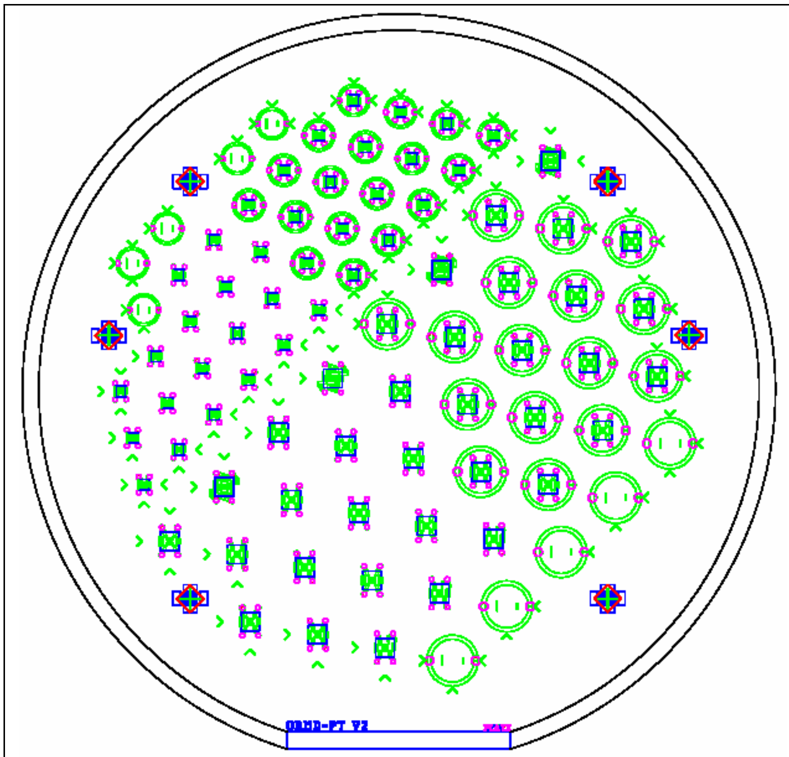

Figure 11: Mask drawing showing multiple layers (each color) for each mask.

MEMS Fabrication

The actual fabrication of the MEMS die was completed, as designed, and incorporated the optimized componentry. The general sequence of MEMS processing steps is as follows:

- Serialize wafers
- Grow and pattern dielectric film
- Etch diaphragms
- Deposit and pattern heaters

- Deposit and pattern sensor element traces
- Deposit and pattern protective coating
- Deposit and pattern electrical connection pads

The specific process recipes were detailed by the MEMS fabrication vendor and were reviewed both internally and with the vendor to minimize errors.

Several experiments were conducted on key processes prior to the final run to minimize risk during the final run. Unfortunately several delays were experienced from the vendor that caused the MEMS run to be significantly delayed. The run was completed in February 2008 and sensing elements were received in March.

Task 5 Evaluate Alternate Technology Options

Orbital Research evaluated an additional pressure sensor technology that appeared promising for combustion pressure sensor applications. This technology, based on thick film fabrication of capacitive sensing elements offers an opportunity to reduce technical risk and increase likelihood of implementing a pressure-based control system for diesel engines.

Fabrication methods for this pressure sensor technology have been established, and the technology is patent pending. Under this task modeling was completed to allow rapid design of a sensor that is appropriate for the pressure ranges of interest in diesel engine combustion. Modeling indicated that the sensor would be too large for the targeted application.

Task 6 Build "Gen 2" Package and Evaluate Critical Assemblies

During this task, Orbital Research fabricated and assembled the second generation package, based on the conceptual development that had been previously accomplished. Detail drawings for each of the sub-components were revised and completed. The solid model renderings are included in the following **Figure 12**. Successfully completing this task required some relatively simple tasks, such as purchase of sub-assembly components. It also required demonstration of some specific technology stepping stones, such as the attachment of the die to the housing package. Detailed plans, with risk mitigation options were incorporated into the planning process.

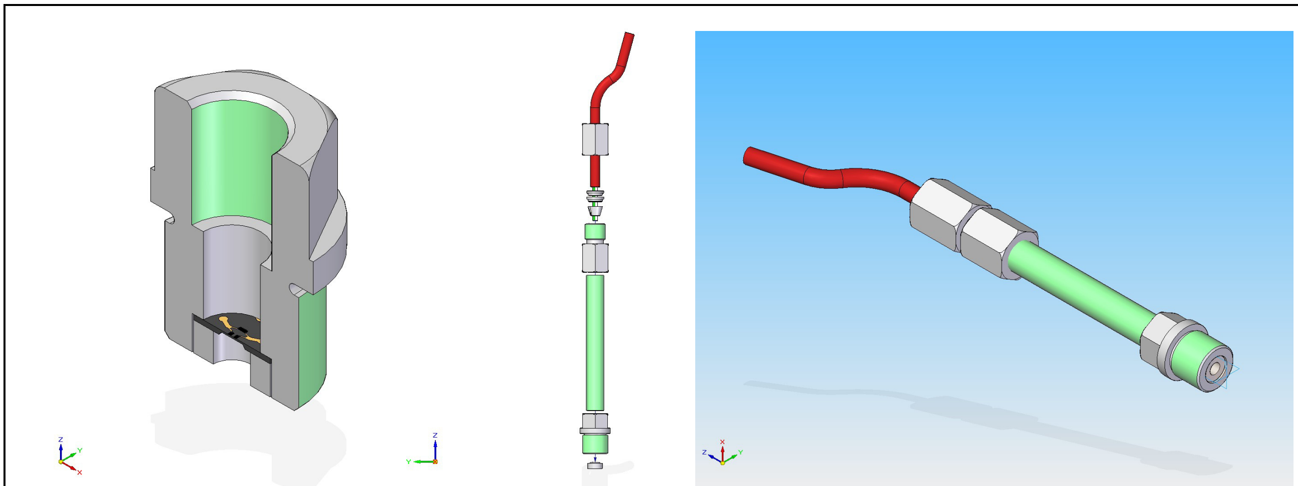

Figure 12: Solid model showing the sensor package and final assembly of the diesel engine combustion sensor.

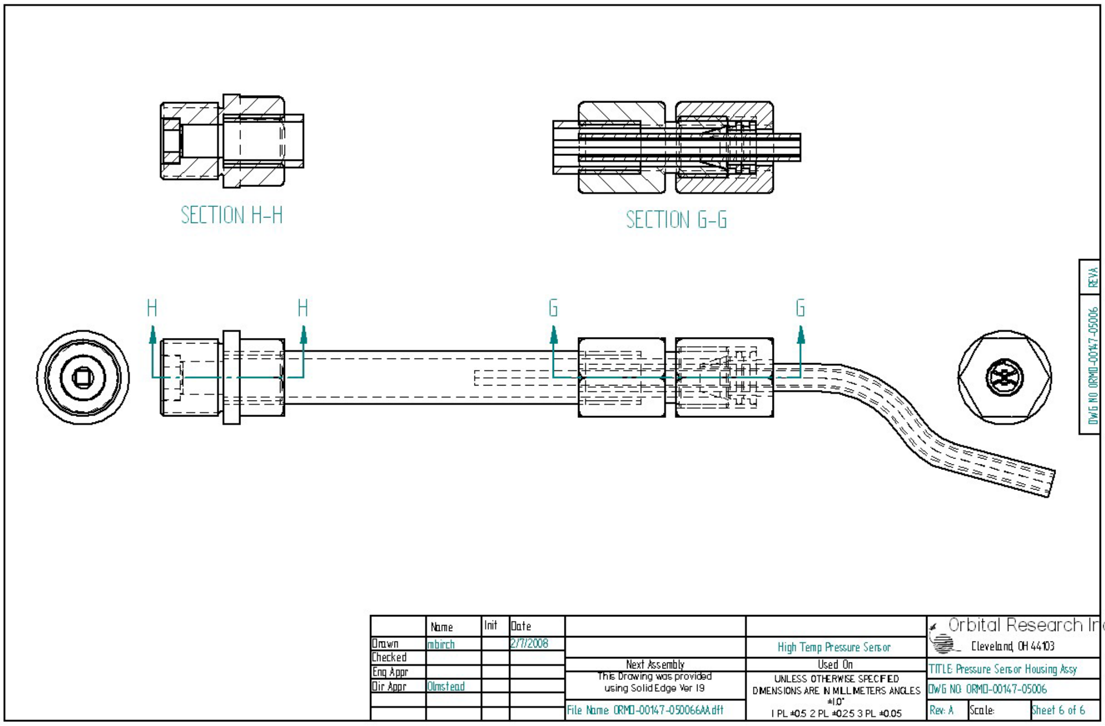

Figure 13: Schematic drawing of the second generation sensor package.

Build Complete Package

Figure 14 shows a partially assembled sensor before the lead wires are retracted into the housing and before the bonding process between the sensing element and the housing. After each of the sub-assemblies had been individually built and tested, the final assembly of all of the components into complete and functional sensors was relatively straightforward. **Figure 12** shows an exploded view of the sensor assembly drawing with a photograph of the final assembled sensor shown in **Figure 15**.

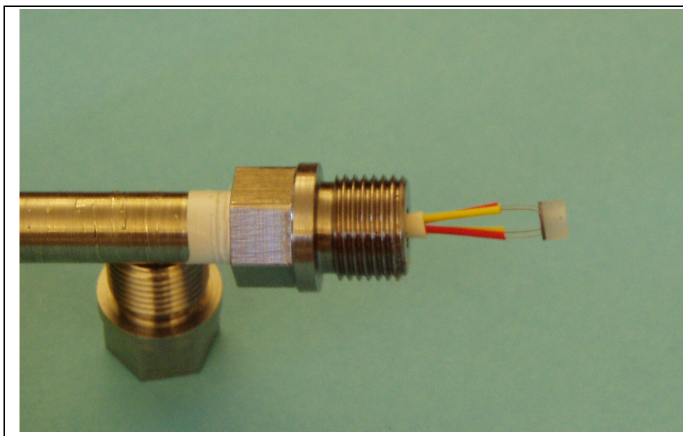

Figure 14: photograph showing sensor during assembly.

Task 7 Perform Laboratory and Engine Testing

The ultimate success of the program is not dependent on the ability to optimize designs, nor to effectively build sub-assemblies and sensors, but rather to demonstrate that the sensors function as anticipated, and can therefore enable the advanced engine management schemes that are already known to reduce toxic emissions.

In this task the sensor functionality was demonstrated, first in the laboratory, then in engine tests of increasing duration.

Pre-Functional Qualification Testing

Pre-functional qualification testing entailed simple checks that each sensor survived the overall assembly process intact. Tests included proof testing of the die with respect to pressure, documenting continuity and resistance of the heater, documenting continuity and resistance of the sense elements, and ensuring that there was still electrical isolation between the heater and the sense element.

Figure 15: Photograph of an assembled sensor package and electrical connections.

Initial Functionality Testing

The goal of this task was to show two things: first that the sensor delivers an output voltage as a function of applied pressure, and second that the heater is effectively heating the sensor. This check was performed, and, as expected, was quite quick.

Calibration

Calibration of the sensors was conducted using compressed gas from a nitrogen cylinder to pressurize both the combustion sensor and a reference sensor. The output of both sensors was measured as a function of pressure and across a variety of control and environmental temperatures. The results obtained were used to calibrate the electronics package that is part of each sensor. The results are an output that is easily measured (amplified signal) and is directly proportional to the pressure. **Figure 16** shows a typical curve.

Sensor-to-sensor comparisons were also performed to determine the reproducibility of the sensors and the extent to which each one will need to be individually calibrated at this stage of product development. The calibration curves were very similar among the sensors. This indicates that the sensors are reproducible, which is good.

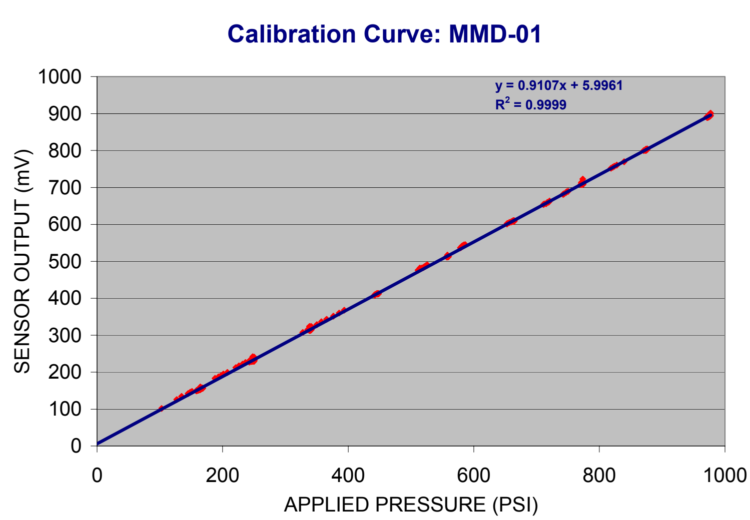

Figure 16: Typical calibration curve showing sensor output compared to the Omega reference sensor pressure measurement.

Laboratory Performance Evaluation

The longer term performance of the sensors was successfully evaluated under controlled conditions. Factors that were evaluated include the durability of the sensor, the stability of the calibration, and the ability to withstand extremes of temperature and pressure outside of the anticipated operating

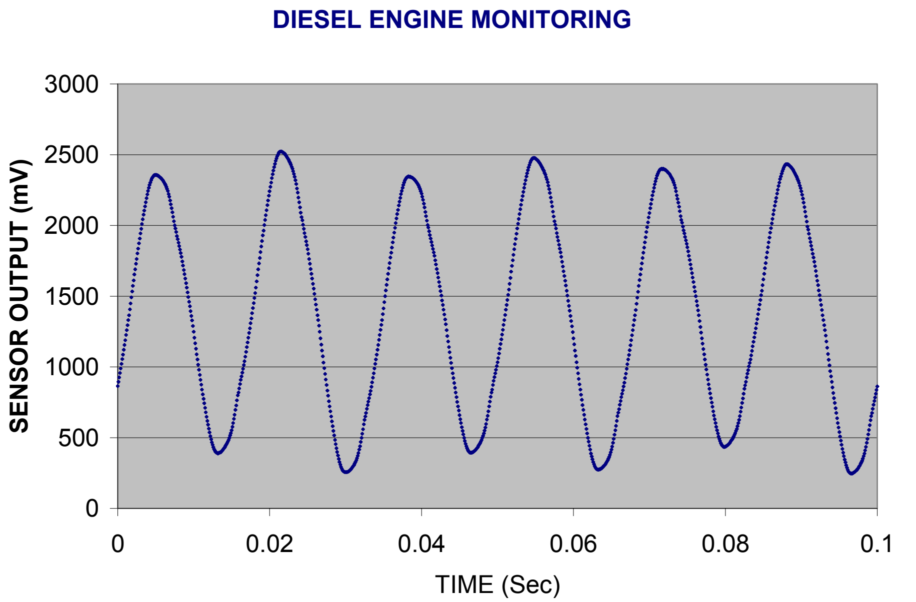

Figure 17: Sample of sensor output while monitoring diesel engine combustion. Sample rate 10k Hz.

regime. The sensors showed linear performance and were well within the anticipated range.

Initial Engine Evaluation

Initially each sensor was tested in a commercially available diesel engine connected to a generator. Sensors were tested for approximately one million combustion cycles to provide confidence that the sensors can withstand environmental stresses in addition to the thermal and pressure stresses. This testing also enabled a demonstration of the sensitivity enhancement that is expected relative to the earlier versions of the sensor. (**Figure 17**)

Extended Engine Evaluation

Engine and engine management system manufacturers have indicated that demonstrating 100 hours of stable survivability is a key benchmark for beginning talks on long term adoption. During this project multiple samples were tested to that benchmark. During these runs samples were removed from the test at regular intervals and the calibration was re-checked. There was no noticeable change in calibration during the duration of the testing. This means that the sensors continue to work the same way after time, which is very important. **Figure 18** shows several calibration curves superimposed on the same graph.

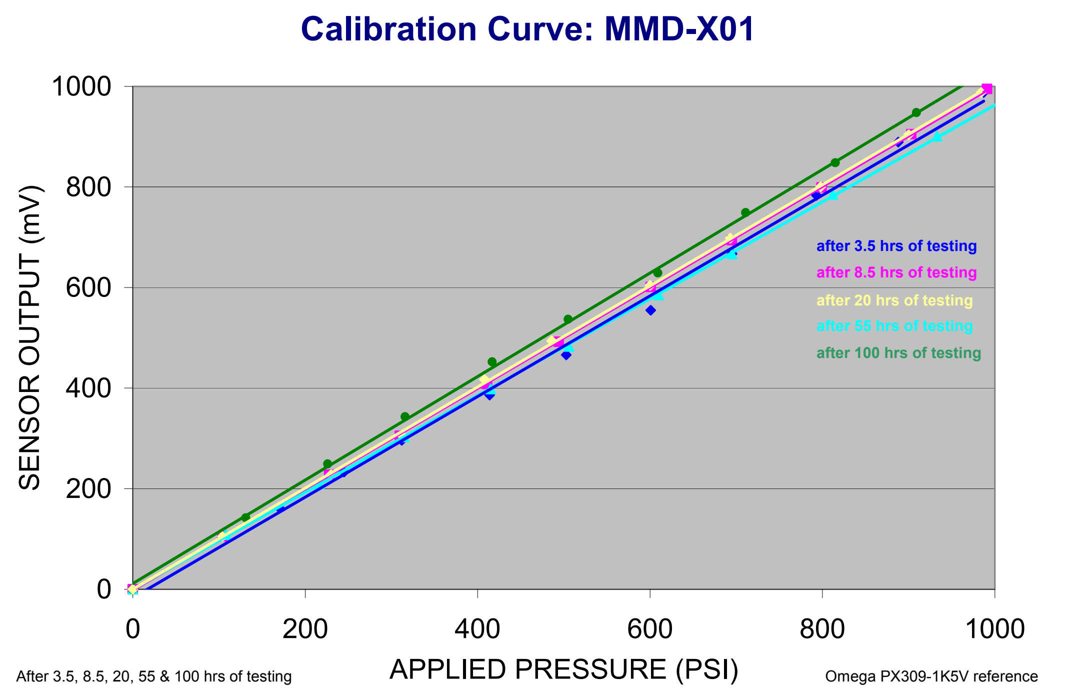

Figure 18: Comparison of calibration curves measure at various times during an extended engine test.

Confirm Effectiveness

The ability of the sensor to measures changes in the combustion process due to less than ideal operating conditions. Comparisons of sensor measurements made while the engine was operating well and when not operating well showed that these sensors can be effective for engine control. Pending additional funding or by working with an OEM partner, future work will target measuring and controlling polluting operating conditions by developing the relationship between the measured pressure profiles to the pollution emission in the engine-out exhaust. This aspect of engine control has been developed by the engine manufactures and is tightly held. Several manufacturers have even patented the engine control strategies based on in-cylinder pressure.[6]

[6] United States Patents: 7,373,918, 7,120,536, 7,000,596, 6,598,468, 6,354,268, 5,642,705, 4,919,099, and 4,397,285 are examples.

4. Conclusions

Orbital Research conducted this project and completed all tasks proposed. Many technical advances were made and the metal alloy sensing element was optimized for both 750 psi and 3000 psi operation. A novel heating element was integrated into the sensor design and optimized for a combination of thermal measurement and control. The mechanical design of the sensor again was optimized and the MEMS manufacturing method was improved. The level of manufacturability still needs to be improved to meet the challenges of commercialization. Additional sources of funding are being pursued to address these critical issues. Testing of the sensor confirmed the technical success of the program. Sensors were tested both in controlled laboratory environment and in diesel engine.

The research was successful in creating a prototype design. The prototype successfully demonstrated methods for manufacturing the sensor system, and was especially successful in completing the demonstration of all of the various aspects of packaging that will allow the senor to be readily manufactured and inserted into engines to facilitate control. Specific successes included mastering the materials and processes necessary to attach the electrical connections and the technology to attach the sensor itself to the package that gets inserted into the engine. The latter required redesign of critical portions of the sensor manufacturing and demonstration of several new technology processes, each of which was successful. The sensor itself, with a substitute thin film component, was successfully demonstrated in an engine for a total of more than 100 hours. The prototype sensor had higher sensitivity than anticipated.

The technology, as demonstrated through the prototype, could be commercialized through early adopters for analytical applications. The engine performance traces that were presented in this report indicate that the sensor will provide adequate information for engine analysis and control. The "backend" of the package will need to be refined to enable extensive commercialization. Fleet application, as compared to laboratory/analytical application, will require that the entire system be miniaturized relative to the prototype. While resources will be required to accomplish that, no development or scientific breakthroughs are foreseen as necessary.

The prototype should be able to be competitive with respect to existing technology. The relative immaturity, as would be expected with any new technology offering, should be offset by the inherently lower production costs should competitive volumes be attained. These projected cost savings are recognized through the use of existing capital facilities for manufacture and the inherent simplicity of the design.

Fuel savings and emission reduction will be realized by extensive integration of the technology into fleet vehicles. The ability to save fuel while reducing emissions is not different from other pressure sensors, but is enabled when the projected cost and price points are achieved, enabling the extensive integration that has been targeted. The fuel savings has been estimated in earlier, comprehensive studies at 2-5%, dependent on operating conditions. "Engine-out" emissions (as compared to final exhaust emissions) are expected to approach Tier 3 levels. This will dramatically reduce the dependence on particulate matter traps and NOx reduction catalysts, reducing those costs dramatically or eliminating them altogether. These savings, in addition to the fuel savings, are anticipated to drive the market towards adoption of the technology.