Reverse Technology Transfer, a Case Study: Use of Automotive OF sensors in Rocket Applications

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The low number of production units and high development costs of aerospace technology products generally result in very high unit costs when compared to other industries. There are many opportunities for adaptation of non-aerospace solutions to aerospace applications that enable significant cost-savings and performance gains. This paper presents the case of using automotive Oxidizer/Fuel sensing technology in rocket engine applications. The use of solid state automotive OF sensors for the measurement of rocket engine OF ratios is discussed, both for testing and flight applications. A technology development program is described that results in a fully commercial product in 30 months.

Nomenclature

AFR	=	Air to Fuel Ratio
DAQ	=	Data Acquisition
GOX	=	Gaseous Oxygen
λ	=	AFR/AFR_{stoic}
OF	=	Oxidizer to Fuel ratio
O2	=	Oxygen
CO	=	Carbon-monoxide
CO2	=	Carbon-dioxide
PID	=	Proportional Integral-Derivative
PWM	=	Pulse Width Modulation
V	=	Voltage

I. Introduction

Historically, the aerospace industry has been an incubator of new technologies, which are then adapted to other mass-produced purposes (e.g., memory foam). However, with the growing number of smaller sized aerospace businesses, and the increasing focus on cost reduction, the situation has now been reversed. Large industries – like the automotive industry – command vastly greater R&D budgets than small-scale aerospace suppliers, and the technologies developed in those industries hold many opportunities for successful adaption to aerospace applications. This paper discusses the adaption of automotive O2 sensors to rocket applications.

Both for the testing of new rocket engines during the development phase, as well as in-flight telemetry of operational engines, the engine Oxidizer to Fuel (OF) ratio is a key performance parameter in bi-propellant designs. OF ratio is tightly coupled to engine performance (achievable specific impulse), propellant gauging and management (minimizing propellant residuals in flight), and safe engine operation (a large OF spike can be used as an early warning system for imminent engine failure). Presently, rocket engine OF is determined by measuring propellant flow into the engine, or optical plume analysis. Both methods are complex (large number of measurements and corrections), require expensive hardware, and are thus limited in achievable precision; especially in a flight environment where weight savings are of paramount importance.

In contrast, all cars currently in production (and the majority of cars produced after 1980) use a direct Air/Fuel sensor, commonly referred to as an O2 Sensor. The O2 Sensor is part of the emissions control system and feeds data to the engine management computer. The purpose of the sensor is to help the engine run as efficiently as possible while producing as few emissions as possible. The very large production numbers of modern automobiles have enabled an extensive investment into the development and refinement of this technology, with resulting O2 Sensors being highly precise, inexpensive (<USD 500), and highly reliable in long-duration harsh environments.

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II. Automotive OF Sensing

Automotive gasoline engines burn hydrocarbons in the presence of oxygen. There is a particular ratio of air and gasoline that is ideal for minimum emissions and optimal fuel economy (approximately 14.7:1 depending on gasoline type and application). A lower ratio than optimal (termed “rich”) will result in unburned fuel remaining after combustion, resulting in excessive emissions and poor fuel economy. A ratio higher than optimal (“lean”) tends to produce more nitrogen-oxide pollutants, can cause poor performance, and can result in engine damage.

The O2 Sensor is typically positioned in the exhaust pipe, with the sensing element exposed directly to the exhaust gas stream. In most applications, the sensor is capable of measurements only within a narrow region centered on the stoichiometric point ($\lambda = 1$) where all fuel is combusted without any excess oxygen remaining. These types of sensors are referred to as Narrow-Band O2 Sensors and are available for approximately USD-25. In high performance applications, more capable Wide-Band O2 Sensors are used, capable of reading a large variation of the OF ratio with great precision at very high sampling rates. There are several companies that specialize in the motorsport applications of Wide-Band O2 Sensors, with systems available around USD-500. In particular, Innovate Motorsports[2] has recently come to market with their “direct digital” Wide-Band O2 control system, which enables exceptional accuracy and response times.

A. Sensing Element

A Wide-Band O2 Sensor (Figure 1) has a solid state O2 pump that can drive oxygen in to or out of a measurement cell based on a supplied pump current. The pump current is supplied by the associated sensor control electronics. The measurement takes place in a special measurement cell (Nernst cell) in the presence of a platinum catalyst. In a rich mixture there is no free oxygen (O2) remaining in the exhaust gas, so the Nernst cell generates a high voltage. The controller sends current through the pump, supplying O2 which reacts with the unburned fuel. The presence of the platinum catalyst is required in hydrocarbon fuel applications, where it enables the combustion of carbon monoxide. When enough O2 has been driven into the measurement cell the Nernst voltage drops. The controller kept track of how much O2 was supplied to use up the remaining fuel and calculates the original (rich) OF ratio from that.

In a lean mixture with free O2, the Nernst cell generates no (or very low) voltage. The controller sends current in the other direction driving O2 out of the cell. When the Nernst voltage goes high, the controller knows how much O2 was removed, thus determining the original (lean) OF ratio.

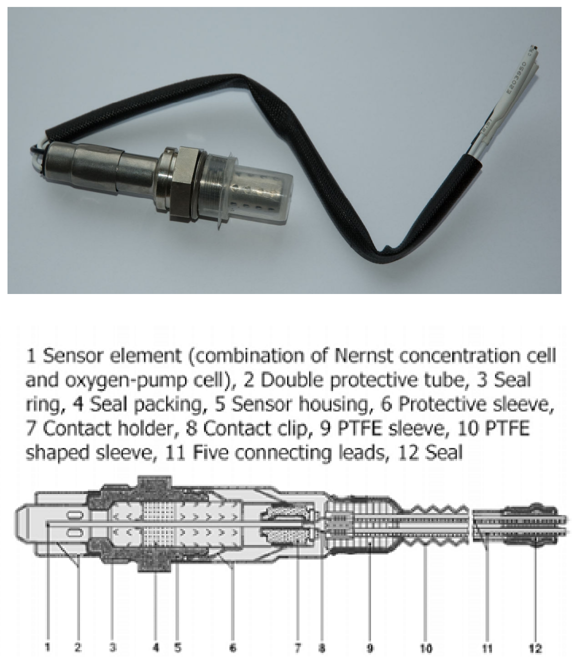

Figure 1: Elements of an Automotive O2 Sensor.
(courtesy of Innovate Motorsports)

Both wide and narrow band O2 Sensors need to be maintained at a specific temperature to function correctly (they are generally heated in automotive applications). In addition, the sensing element must be exposed to both the exhaust gas, and a source of oxygen.

B. Sensor Control

Innovate Motorsports (IM) has developed a new type of control system for automotive O2 Sensors, which significantly improves performance. This method uses the same wideband zirconium-dioxide oxygen sensors as current production vehicles, but the control methodology is completely different. The measurement principle does not use the more common proportional-integral-derivative (PID) feedback mechanism to control the wideband sensor. Instead, the pump current is positive until the reference (Nernst) cell shows $\lambda < 1$ (rich / excess fuel) in the

2 http://www.innovatemotorsports.com/

measurement chamber of the sensor. Then the polarity of the pump current is reversed until the reference cell shows $\lambda > 1$ (lean / excess oxygen). This is done with a small hysteresis; this way the gas sample in the measurement chamber oscillates at about 100-500 Hz around stoichiometric. The oscillation frequency depends on the constant amplitude (but changing polarity) pump current, hysteresis, the sensor itself, and λ. The frequency has a maximum at $\lambda = 1$.

Because of the oscillation of the measurement cell using this approach, there is no equilibrium state in the cell which would slow down the diffusion and decrease sensor response. In addition, there is no electrostatic charge buildup on the measurement cell that causes drifts during operation at $\lambda < 1.0$. Lastly, conventional PID sensors have a singularity at $\lambda = 1$, which causes instabilities in the normal PID feedback mechanism; the IM method does not show these instabilities. A conventional PID feedback loop needs to be tuned to the speed response of the controlled system. The best one can do is to achieve critical damping, otherwise wild oscillations and over swings will occur. The IM approach on the other hand makes specific use of those oscillations by running the feedback loop deep into those normally undesired oscillations. The end result is a highly responsive system, with response times reduced by over one order of magnitude (Figure 2).

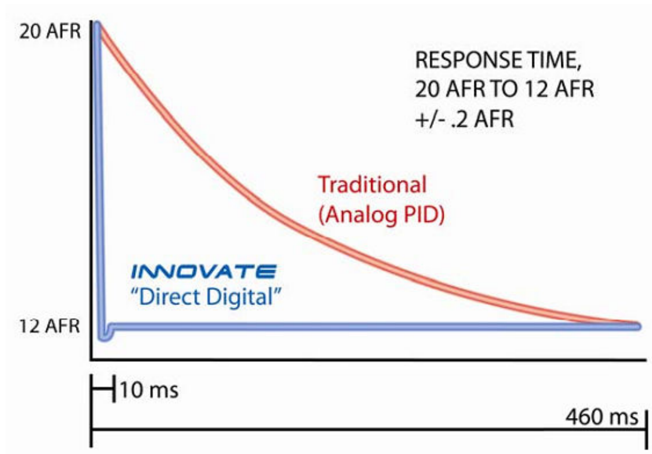

Figure 2: Sensor response time vs. AFR.
(courtesy of Innovate Motorsports)

III. Rocket Engine OF Sensing

Both for the testing of new rocket engines during the development phase, as well as in-flight telemetry of operational engines, the engine Oxidizer to Fuel (OF) ratio is a key performance parameter in bi-propellant designs. OF ratio is tightly coupled to engine performance (achievable specific impulse), propellant gauging and management (minimizing propellant residuals in flight), and safe engine operation (a large OF spike can be used as an early warning system for imminent engine failure).

A. Survey of Approaches

Presently, rocket engine OF is determined by measuring propellant flow into the engine through various means, or by optical plume analysis. Both methods are complex (large number of measurements and corrections), require expensive hardware, are thus limited in achievable precision, and need to be calibrated to a very specific set of operating conditions. In addition, for in-flight applications (propellant management, integrated health monitoring) these systems are lacking in robustness, have high complexity/parts-counts, and undesirably high weight (Table 1).

Table 1: Methods of real-time OF ratio sensing, and their applications / characteristics.

Method	Sensor	Propellant Phase†			Response	Complexity	Weight	Cost
		G	L	M				
Mass Flow	mechanical P/T/Level ultrasound	☑	☑		Slow	Medium	High	High
Optical Plume Analysis	Laser/Optical	☑	☑	☑	Fast	High	Medium	High
Direct OF Sensing	Solid State	☑	☑	☑	Fast	Low	Low	Low

†*Propellant Phases: G = Gas, L = Liquid, M = Mixed*

The most common approach in OF determination is through measurement of propellant mass-flow; once the mass-flow of propellants into the engine is known, the OF ratio is determined by the ratio of oxidizer and fuel mass-flow data. There are a variety of mass-flow transducers available, including thermal, mechanical, vortex shedding, venturi, optical, and many others. Another approach is to measure propellant tank pressures, temperatures, and liquid level (individually or in combination) and calculate the change in propellant mass based on assumptions of the system state (propellant phase uniformity, mixing, tank geometry, steady-state flow in propellant lines, etc).

All of the mass-flow based OF measurement approaches have inherit disadvantages. Since the OF value is deduced from a number of measurements (and not measured directly), response time is slow and the measured value is not always representative of the actual operating state of the engine. While mass-flow measurement is generally effective for propellant management applications where the signal is integrated over time, mass-flow is unsuitable for real-time / in-flight applications where OF is used to monitor the health of the engine and the system is intended to respond sufficiently quickly to achieve safeing in the case of engine malfunction. The large number of transducers (which can be of significant size) drives up system weight and cost, while impacting system reliability.

Figure 3: A very large coriolis flow-meter. *(courtesy of ABLE Instruments & Controls)*

Mass-flow based OF determination also is not suitable for mixed-phase (gas/liquid) applications, and generally requires knowledge (or assumptions) on the state of the propellant both in the tanks and in the feed lines. Volumetric flow metering is proportional to mass flow rate only when the density of the fluid is constant. If the fluid has varying density, or contains bubbles, then the volume flow rate multiplied by the density is not an accurate measure of the mass flow rate. Many mass-flow transducers can cause a change in the fluid they are measuring (e.g. pressure drop, phase transition, bubbles, etc), which degrades their usefulness and accuracy. Lastly, to minimize these effects, flow-meters generally need to be mounted with long, straight sections of piping, which incurs additional weight.

A second approach to real-time OF sensing is optical plume analysis. Through the detection of metals in the exhaust plume, information relative to the degradation of hardware can be gathered (a lean OF will cause metal to be present in the plume from engine erosion). Although spectrum analysis is commonplace in the jet engine industry, the size and weight of the monitoring devices make the application for rocket engines more of a challenge. These types of systems are very accurate, and have excellent response times. However, the sensing elements are complex and need to be ruggedized to function in the severe operating environment. This technology is also very aerospace specific, with low production numbers, and very high costs.

B. Direct OF Sensing

Figure 4 shows a conceptual drawing of how a Direct OF Sensing approach can be applied to a rocket engine. The system has a very low parts count, enabling high reliability and low cost. A separate oxygen supply is shown for vacuum flight applications; this part can be omitted for ground-test applications where atmospheric oxygen is available in sufficient quantities. In a flight application, gaseous oxygen can be sourced directly from the oxidizer propellant. The transducer (O2 Sensor) is sufficiently compact to use multiple sensing elements and multiple pickup

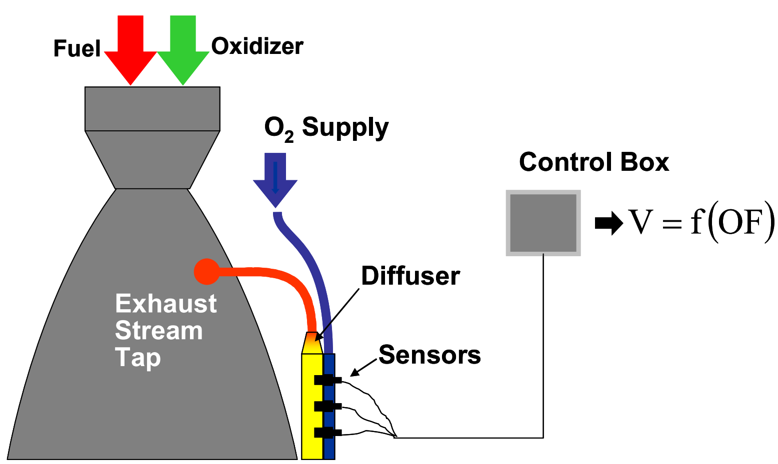

Figure 4: Schematic of OF Sensor on rocket engine.

points on larger rocket engines, which can yield safety-redundancy and valuable insight into engine combustion uniformity. A bend in the exhaust stream tap (or "pig-tail") is used to protect the transducers from excess heat. A diffuser is added upstream of the sensing element to reduce flow speeds and further reduce exhaust temperature as needed to meet transducer specifications. The control box drives the sensor and converts the transducer output into a voltage signal from which OF can be read via a calibration function.

C. Technology Development Approach

Table 2 summarizes a four phase technology development program; each phase has specific objectives, an identified test bed, and associated cost estimate and phase duration in calendar days.

Table 2: Technology development program definition.

Phase	Description	Objectives	Testbed	Cost	Duration
1	Proof-of-Concept	• Demonstrate feasibility • Demonstrate accuracy, response time, reliability, etc.	Bi-prop gaseous thruster (10-50 lbf)	\$100k	6 months
2	Application Survey	• Investigate applications to a variety of propellants (species, gas/liquid/mixed) • Investigate sensitivity to sensor placement	Bi-prop liquid rocket engine (1,000+ lbf)	\$600k	12-24 months
3	Product Development	• Develop commercial product for ground-test applications • Establish supply chain and production • Establish operational support, training, manuals, etc.		\$1.5M	12 months
4	Flight Application	• Develop flight-system • Demonstrate system application	Small Launch Vehicle or Sounding Rocket	\$5Mk	2 Years

Phase 1 is a proof-of-concept activity during which the proposed system is investigated for overall feasibility. Figure 5 shows a schematic of the experimental setup needed for this phase of the development program. A simple oxygen/methane (or other green & storable propellant) gas/gas thruster is used with manual pressure regulators and gas-flow-meters. The data collected from the flow-meters allows for OF determination via the ratio of propellant mass-flows, which is then compared to the direct OF signal to derive a sensor calibration function.

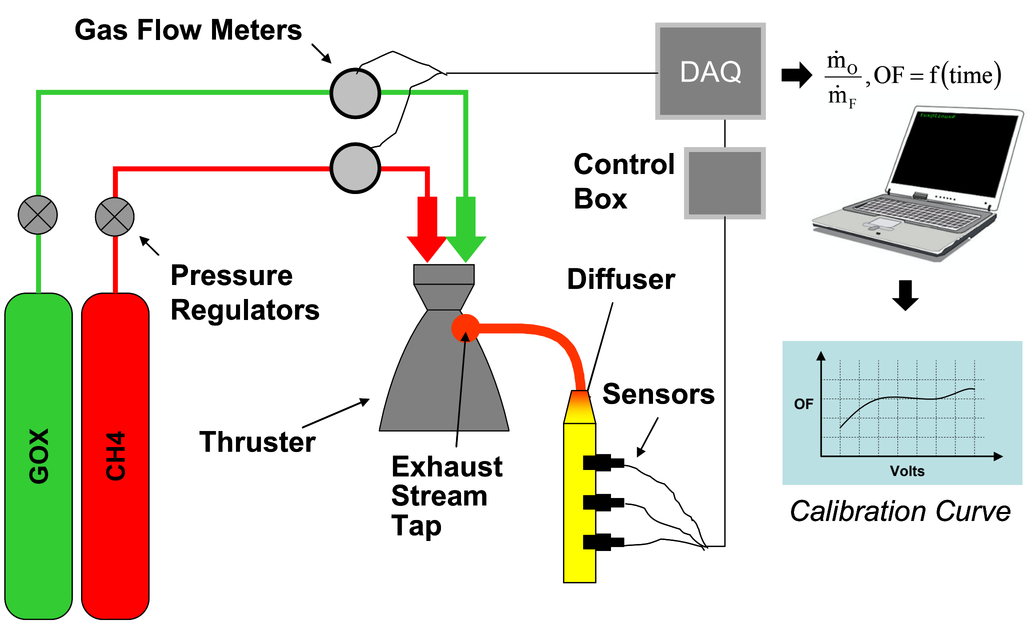

Figure 5: Proof-of-Concept experimental test setup.

The anticipated funding level and duration required to meet program goals are within the range typical for government funded phase one Small Business Innovative Research (SBIR) programs. The scope of the program is also suitable for implementation at an academic institution providing the additional benefits of nurturing young engineering talent.

Phase 2 expands the work completed in the previous phase by investigating the use of this technology with a variety of propellants, both liquid and gaseous. In addition, second order effects such as variations of system accuracy due to placement, thermal environment, etc, are investigated. This activity requires a larger test engine, which allows for the capture of these effects. The ideal placement of the transducers and quality of the exhaust stream at the diffuser exit are also investigated.

Phase 3 develops a commercial product based on the results of the first two phases. This includes the finalized specifications of the transducers and sensor electronics, establishment of a supply chain for the various components, and the creation of training materials (manuals, etc). Following the completion of this phase, the technology is ready for commercial marketing and use in the ground-testing of rocket engines.

Finally, Phase 4 demonstrates the application of the system in a flight environment. This addresses the special considerations for vacuum operation, minimal system weight, and additional ruggedization of the components. At the completion of this phase, the system is fully qualified for flight-applications on all applicable launch vehicles and in-space transportation systems.

IV. Summary

This paper discusses the use of automotive air/fuel ratio sensing technology in rocket engine applications. The high number of production units and rapid product cycles of the automotive industry have resulted in a very capable yet low-cost system that allows for the direct measurement of oxidizer to fuel ratio (OF) simply by exposing the sensing element to the exhaust gas stream. Compared to more traditional approaches to rocket engine OF determination, this direct sensing technology offers many advantages in response time, accuracy, reliability (parts count), size & weight, and cost.

The paper outlines a 4 phase development program that results in a fully viable commercial product, applicable to ground-testing and in-flight applications for a large variety of rocket engines. The initial phase of the proposed program requires only minimal funding and is of appropriate scale for implementation in an academic environment. The ground-use product development portion of the complete development program could be completed in as little as two years, and a flight demonstration of the technology in an additional two years after that.

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