In Situ Multi-Species (O_2, N_2, Fuel, Other) Fiber Optic Sensor for Fuel Tank Ullage

Abstract: A rugged and compact fiber optic sensor system for in situ real-time measurement of nitrogen (N_2), oxygen (O_2), hydrocarbon (HC) fuel vapors, and other gases has been developed over the past several years at Glenn Research Center. The intrinsically-safe, solid-state fiber optic sensor system provides a 1% precision measurement (by volume) of multiple gases in a 5-sec time window. The sensor has no consumable parts to wear out and requires less than 25 W of electrical power to operate. The sensor head is rugged and compact and is ideal for use in harsh environments such as inside an aircraft fuel tank, or as a feedback sensor in the vent-box of an on-board inert gas generation system (OBIGGS). Multiple sensor heads can be monitored with a single optical detection unit for a cost-effective multi-point sensor system. The present sensor technology is unique in its ability to measure N_2 concentration directly, and in its ability to differentiate different types of HC fuels. The present sensor system provides value-added aircraft safety information by simultaneously and directly measuring the nitrogen-oxygen-fuel triplet, which provides the following advantages: (1) information regarding the extent of inerting by N_2, (2) information regarding the chemical equivalence ratio, (3) information regarding the composition of the aircraft fuel, and (4) by providing a self-consistent calibration by utilizing a singular sensor for all species. Using the extra information made available by this sensor permits the ignitability of a fuel-oxidizer mixture to be more accurately characterized, which may permit a reduction in the amount of inerting required on a real-time basis, and yet still maintain a fire-safe fuel tank. This translates to an increase in fuel tank fire-safety through a better understanding of the physics of fuel ignition, and at the same time, a reduction in compressed bleed air usage and concomitant aircraft operational costs over the long-run. The present fiber optic sensor can also be used as a *false-alarm-free* engine/hidden/cargo space fire detector (by measuring increased CO_2 and CO, and decreased O_2), a multi-point in situ measurement and certification system for halogenated-compound fire protection systems, and for the testing and certification of other aircraft safety sensor systems. The technology (LEW-17826-1) developed in the present sensor system is patent pending.

In Situ Multi-Species (N_2, O_2, Fuel, other) Fiber Optic Sensor for Fuel Tank Ullage

Quang-Viet Nguyen
NASA Glenn Research Center
21000 Brookpark Rd
Cleveland Ohio 44135

International Fire & Cabin Safety Research Conference
Tropicana Resort and Hotel, Atlantic City, NJ
Oct. 29 – Nov. 1, 2007

Outline

- Why Measure N_2, O_2, and Fuel?
- Fuel Ignition Studies at GRC
- Genesis for Sensor Concept – Combustion Diagnostics
- Prototype Fiber Optic Sensor System
- Some Results From Bench-top Tests
- Design of a Rugged Flight-Capable Sensor System
- Conclusions

Why Measure N_2, O_2, and Fuel?

- Absolute risk of ignition is always there – cannot be zero
- How much inerting is required for a reasonable level of safety?
- Measurement of Oxygen, Nitrogen, and Fuel Vapor *(volatiles vs. non-volatiles)* gives more accurate indication of Minimum Ignition Energy (MIE)
- The more information available, the better equipped we are to estimate potential for ignition
- Multi-Dimensional Physics-Based Response (Go/No-Go) Surface

- Even if conditions in the fuel tank are susceptible to ignition, what if we can know what the maximum pressure rise is, and decide if it is dangerous?

Why Measure N_2, O_2, and Fuel? Cont'd

- Fuel vapor and O_2 concentration provides indicator of the *inherent chemically-based susceptibility to ignition* (kinetics)

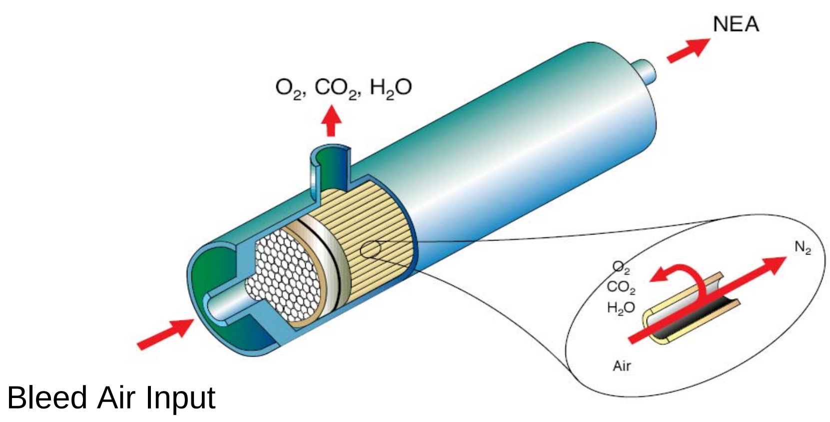
- N_2 concentration provides indicator of *inherent ability of inerting compound to absorb heat in event of ignition* (thermicity)

- Direct measurement of N_2 provides accurate measure of inerting efficiency, and is best for an OBIGGS feedback control system that reduces bleed air usage and ***decreases fuel consumption***

- Measurement of N_2/O_2/Fuel provides comprehensive picture to make informed decisions that ***increases aircraft safety***

- Almost ALL current fuel tank ullage sensors only measure oxygen (O_2)

ASM's Produce Nitrogen Enriched Air (NEA)



NASA/CR 2001-210950 by Reynolds et al.

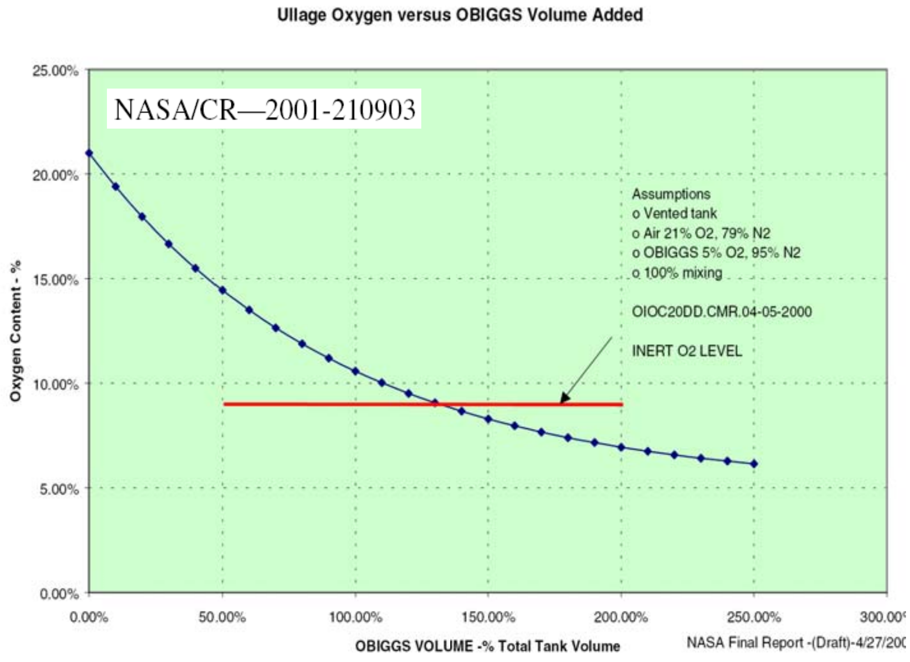


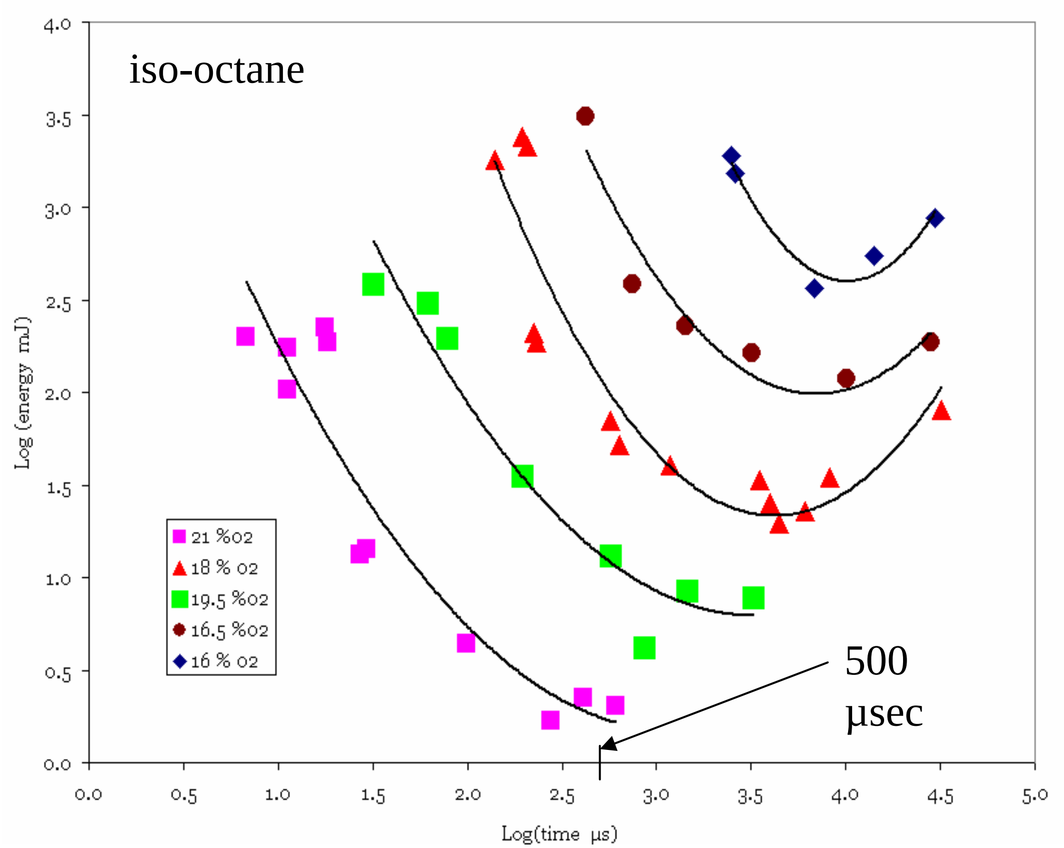
Figure 5.0-36. Ullage Oxygen Versus OBIGGS Volume Added

HFM ASM's require 14 to 35 kg/min of bleed air and 50 to 121 kW of power to inert a typical Boeing 747

Is measuring O_2 alone the best way to predict safety, and provide feedback control of OBIGGS for N_2 generation?

Fuel Ignition Studies at GRC

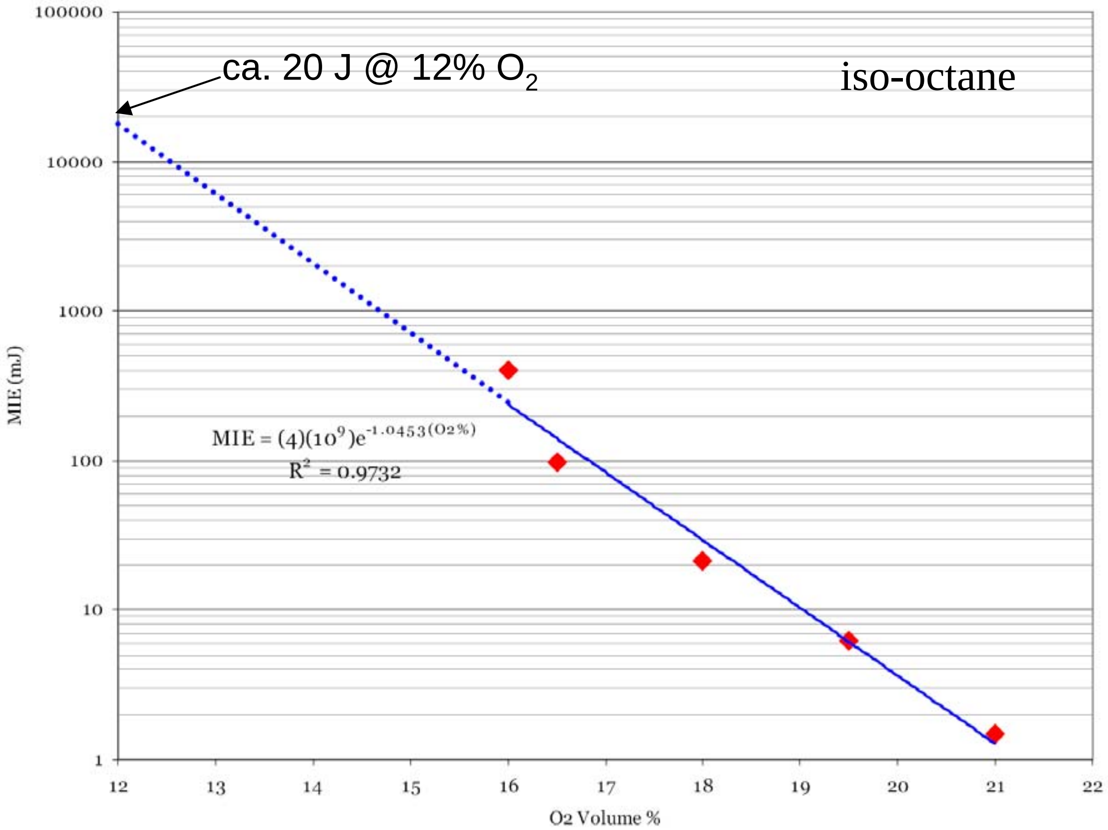
Effect of Spark Duration and Oxygen on Minimum Ignition Energy (MIE) at 14.5 C^0



Data, courtesy M.J. Rabinowitz (RTB), NASA GRC

Fuel Ignition Studies at GRC

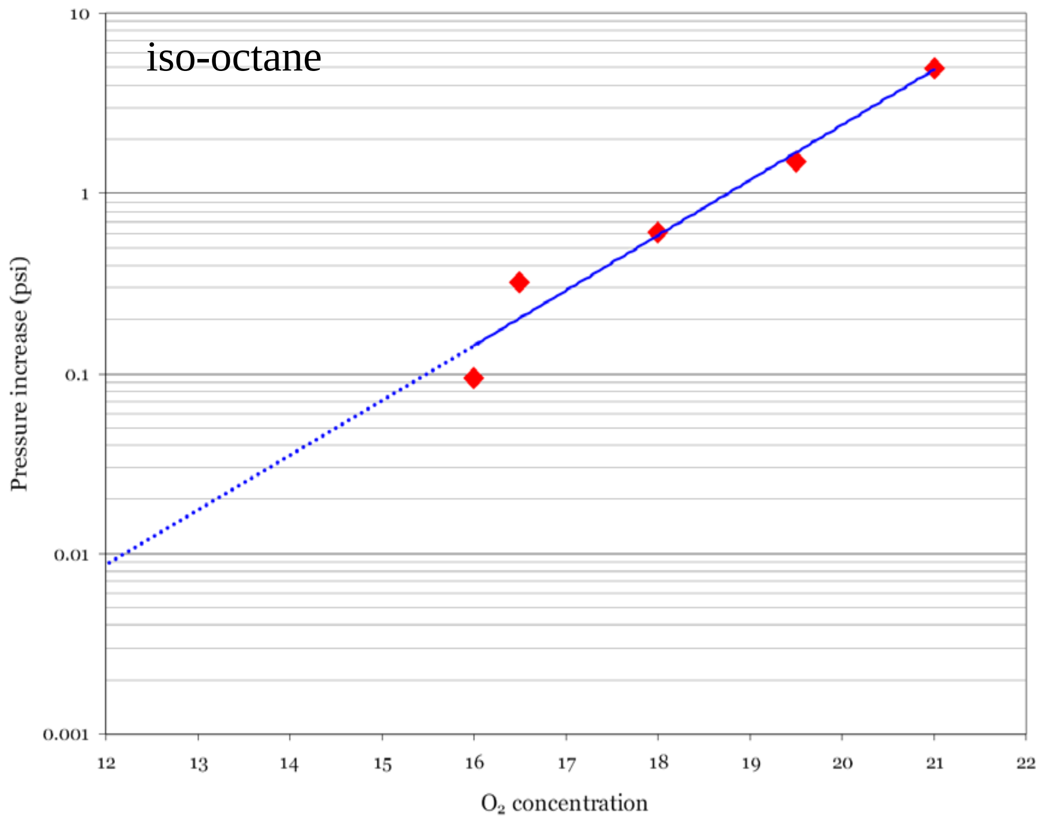
Effect of O_2 on MIE at 14.5 C^0



Data, courtesy M.J. Rabinowitz (RTB), NASA GRC

Fuel Ignition Studies at GRC

Effect of O_2 on Pressure Rise at 14.5 C^0

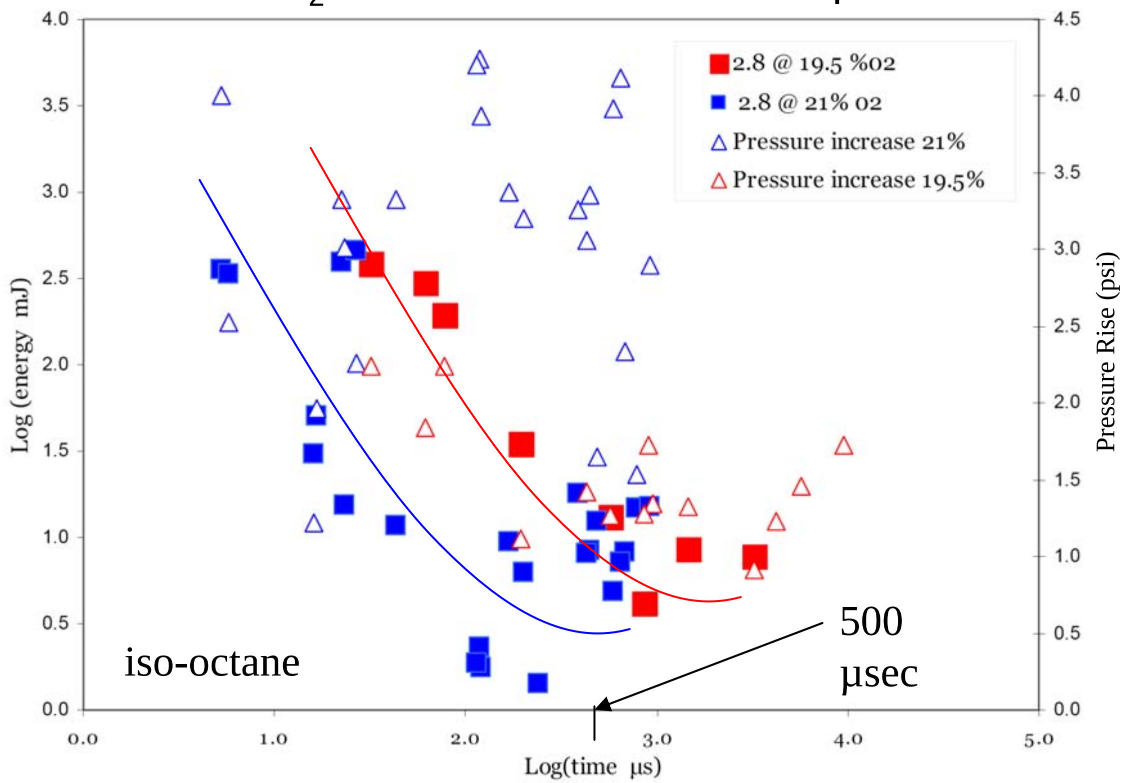


Data, courtesy M.J. Rabinowitz (RTB), NASA GRC

Q.V. Nguyen (RTB), NASA GRC

Fuel Ignition Studies at GRC

Effect of O_2 on Press. Rise at Fixed Equiv. Ratio

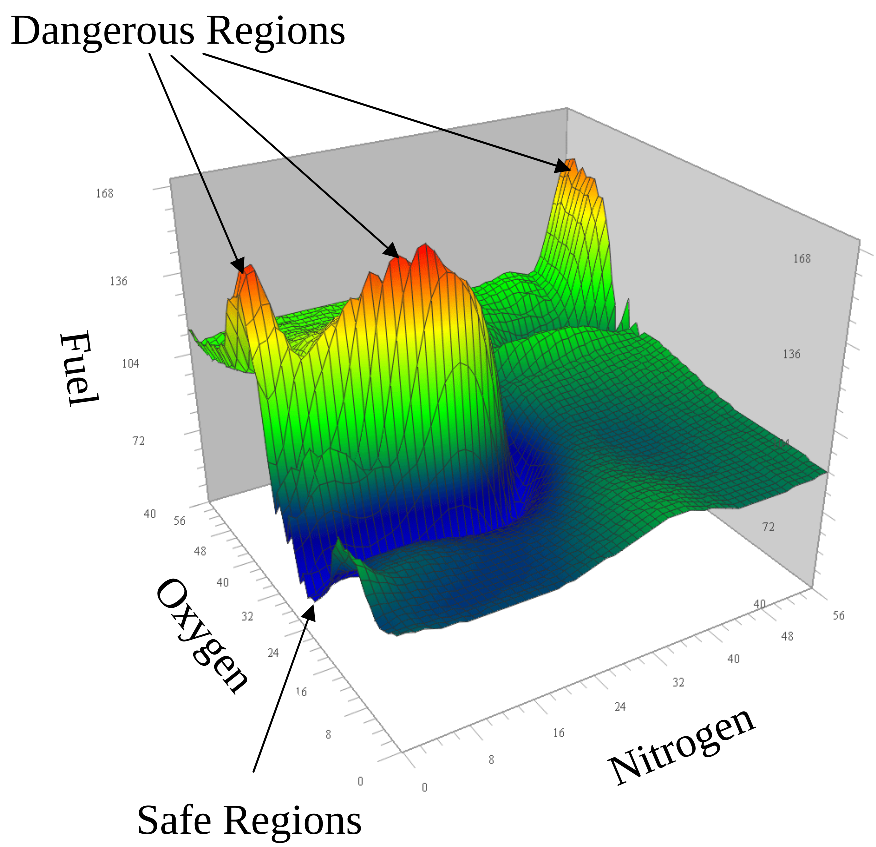


Data, courtesy M.J. Rabinowitz (RTB), NASA GRC

Need a physics-based 'Go/No-Go' decisional response surface

Multi-Dimensional Response Surface

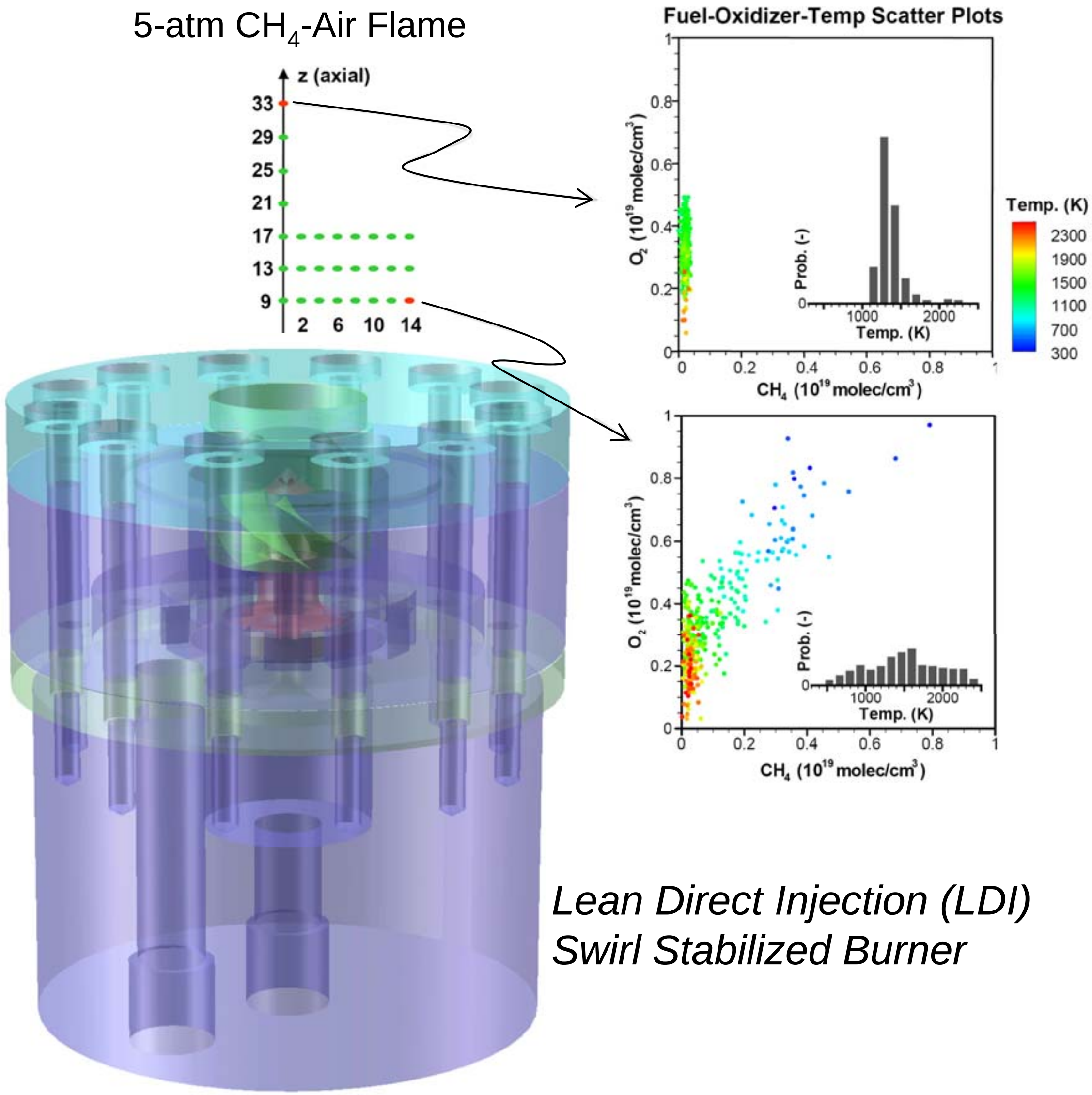
Notional Example of a Response Surface



Inputs:

- N_2, O_2, Fuel, …
- Temperature
- Pressure (altitude)
- Ascending/Descending
- Composition of Fuel
- Humidity,…

Genesis – Laser Diagnostics in Turbulent Flames

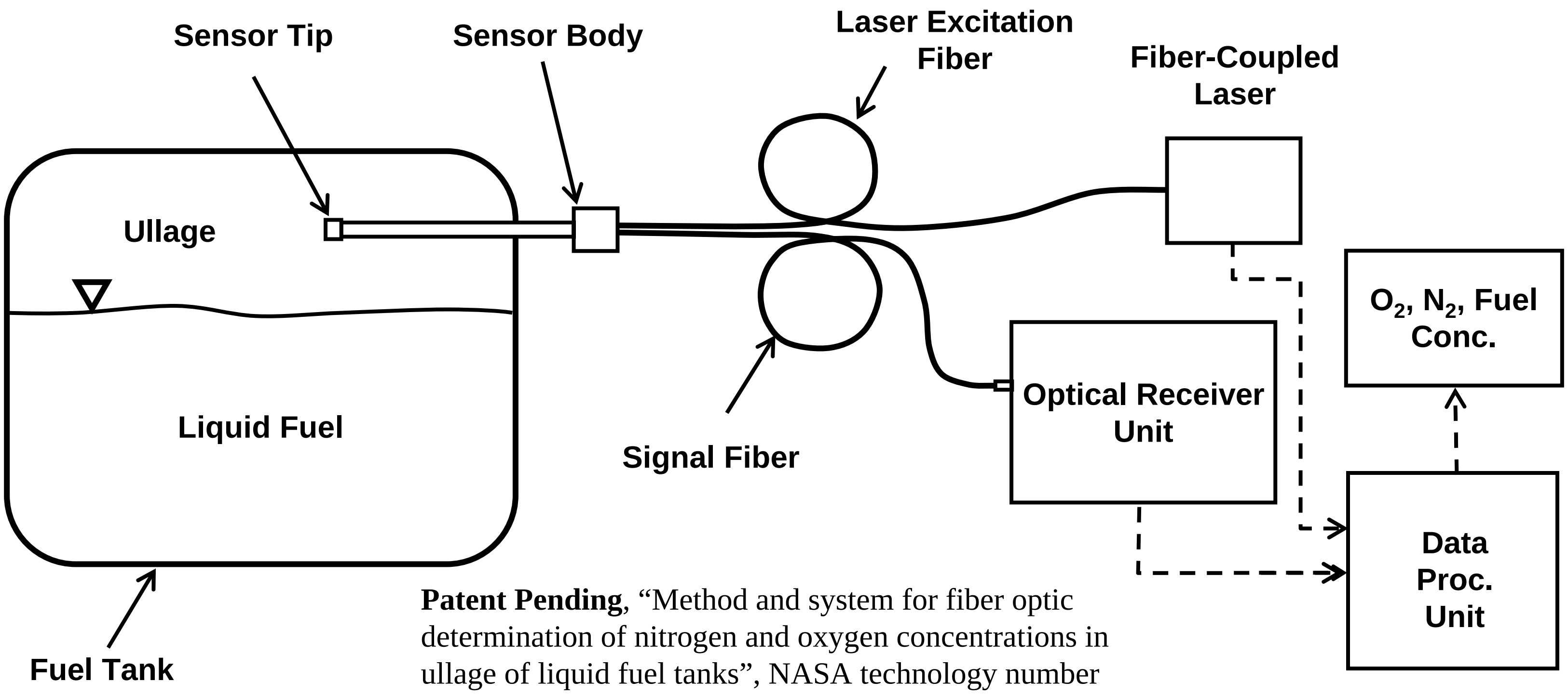


Lean Direct Injection (LDI)
Swirl Stabilized Burner

- Raman scattering is powerful and quantitative multi-species measurement technique
- ***How do we make it cost-effective, practical, and reliable for an aircraft based fuel tank ullage sensor?***

Q.V. Nguyen (RTB), NASA GRC

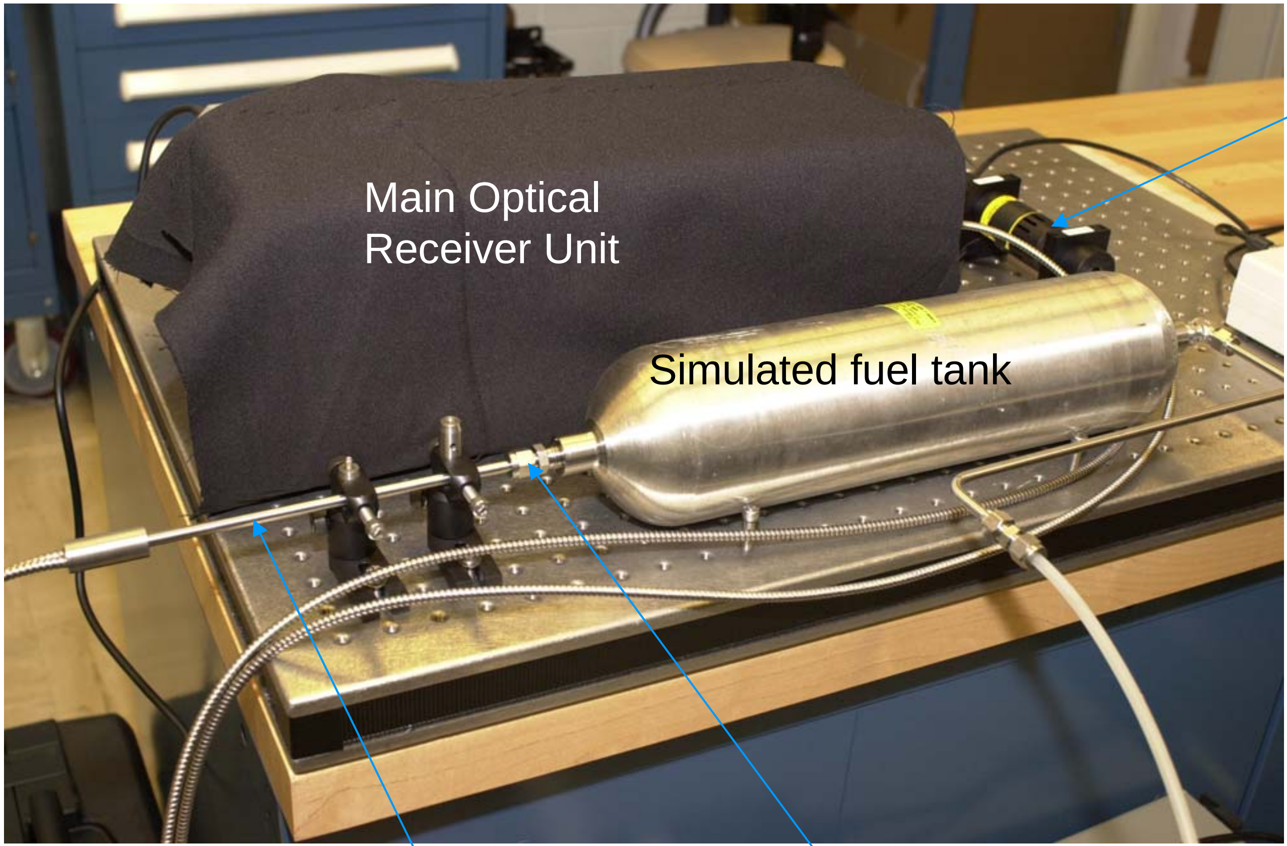
Fiber Optic Sensor System for Fuel Tank Ullage



Patent Pending, "Method and system for fiber optic determination of nitrogen and oxygen concentrations in ullage of liquid fuel tanks", NASA technology number **LEW-17826-1**.

- **Fiber Optic Probe Head:** compact and rugged design fits into tight spaces
- **Laser excitation system:** low-power 30 mW diode laser does not pose ignition danger *(equivalent to15 µJ in 500 µs)*
- **Optical Receiver Unit:** remotely located to avoid harsh environment near fuel tank, permits easy serviceability, can accept multiple probe locations for cost-effective multi-sensor deployment

Breadboard Fiber Optic Sensor System



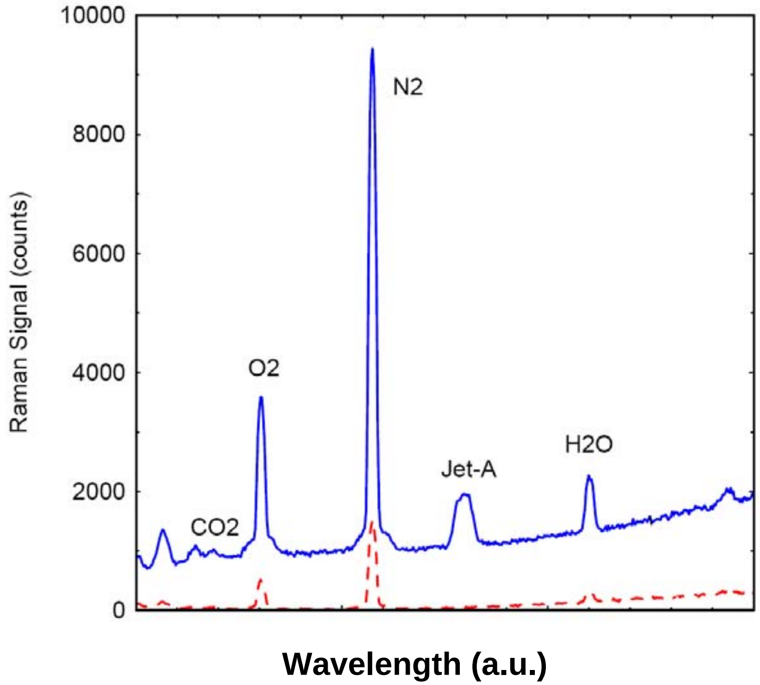
Excitation
Diode
Laser

¼ in Dia.
Stainless Steel
Probe Tip

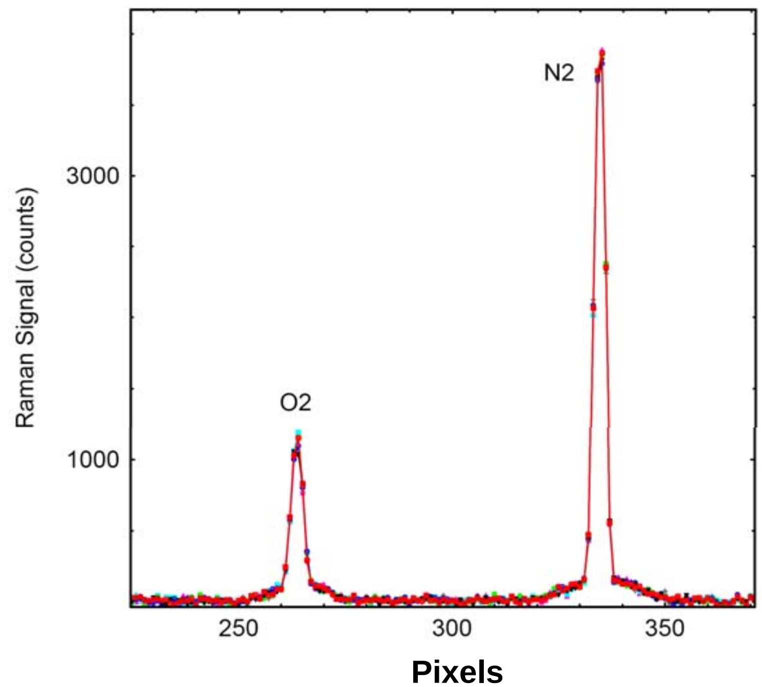
Simple
Feedthrough
Fitting

Raman Scattering of Various Gases

20 sec acq. with 30 mW laser

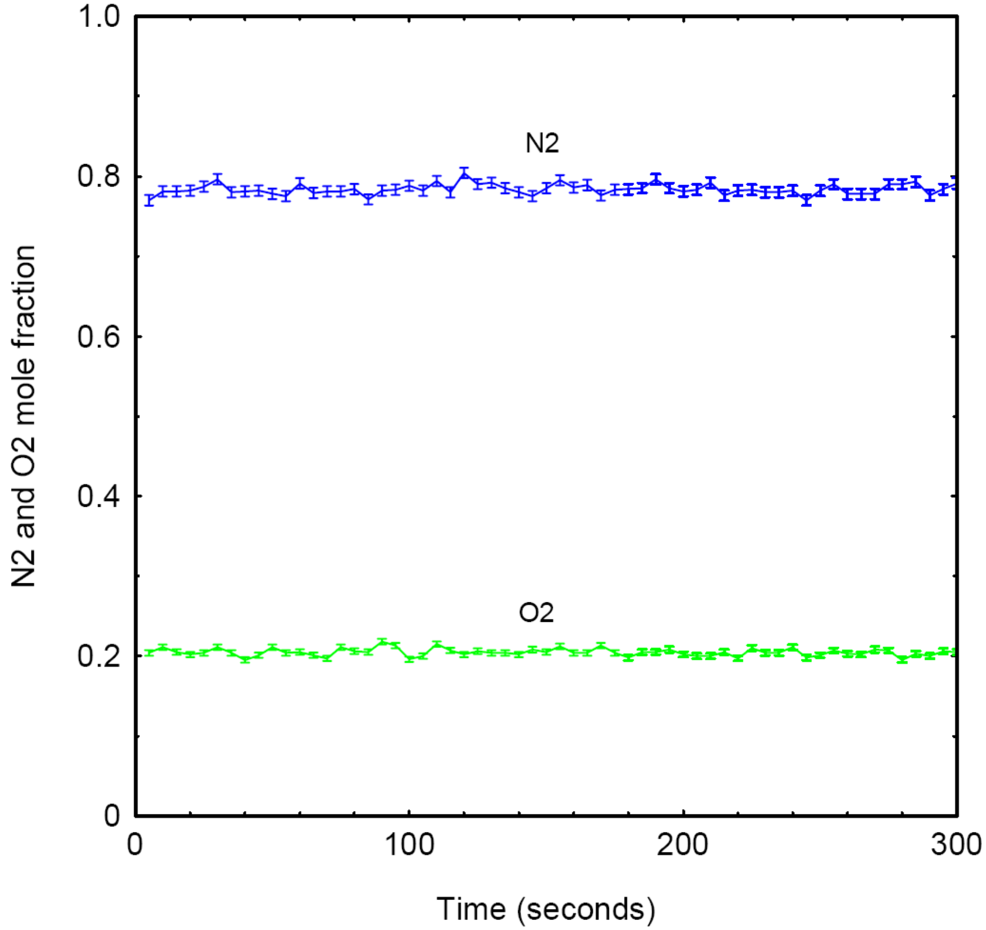


8 different spectra superimposed



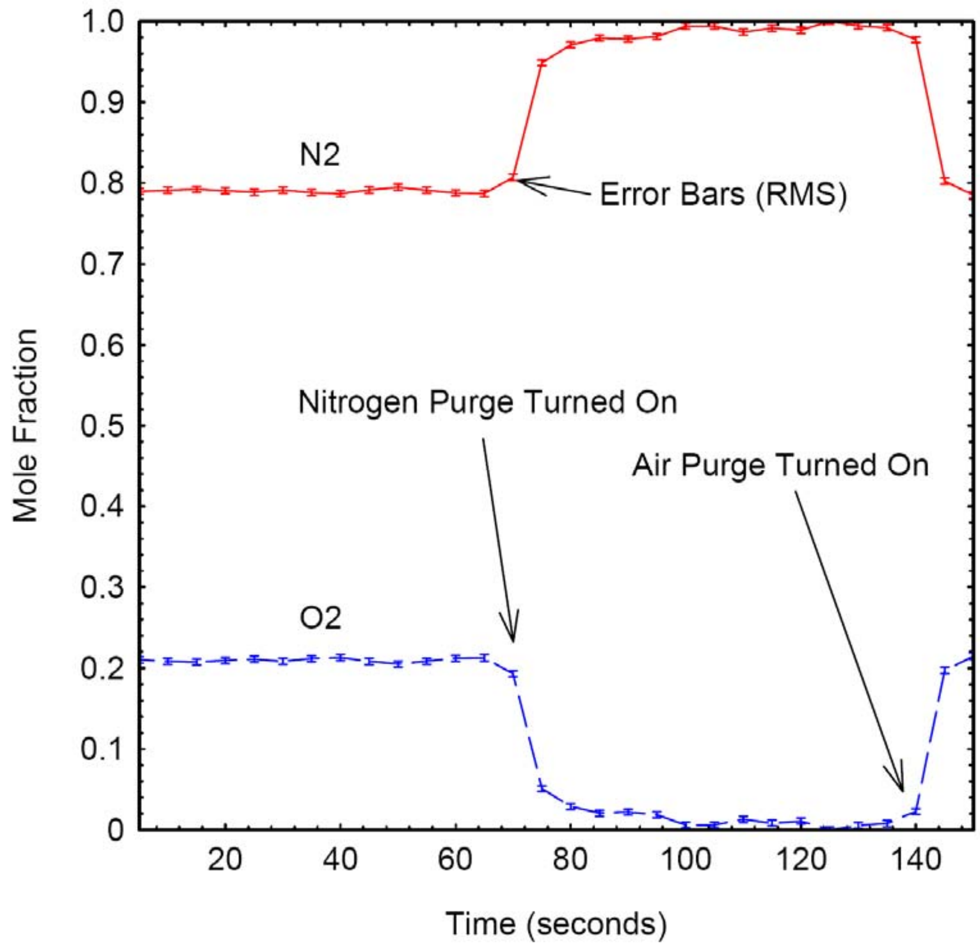
Can also ***differentiate*** the type of HC bonds: saturated vs. un-saturated HC's – volatiles vs. non-volatiles

Measurement Stability in Ambient Air



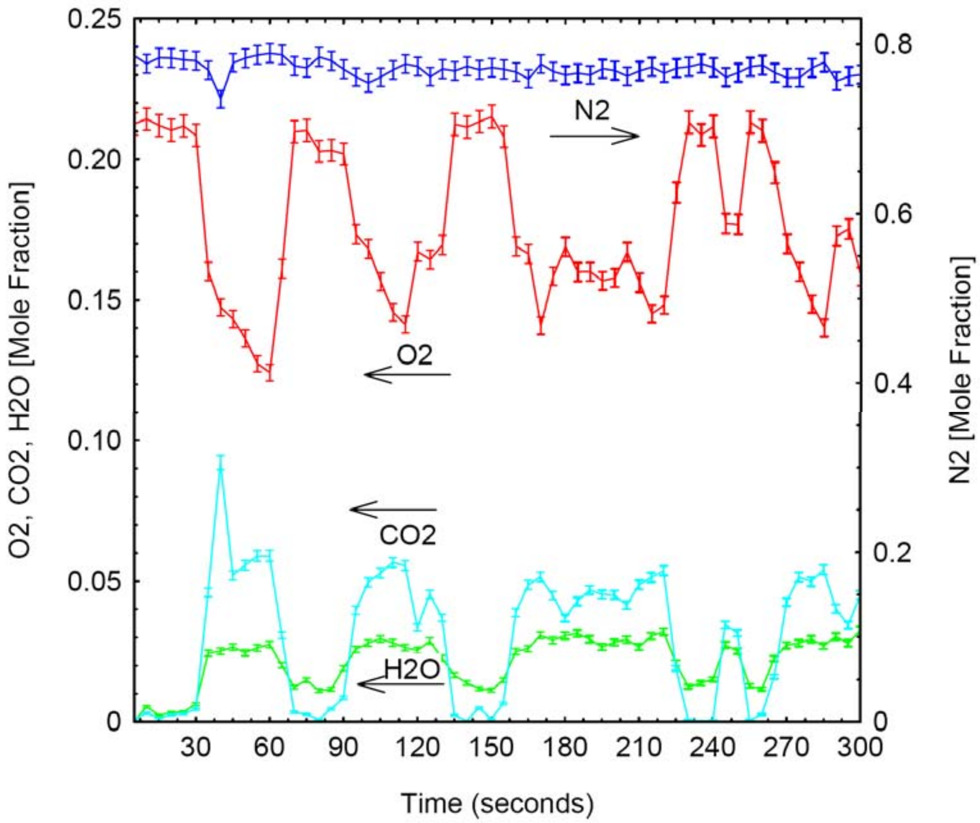
- 5 Hz data rate
- Variations are due to fluctuations in laser power and can be normalized out (not shown)
- Signal obeys Poisson statistics: RMS = Sqrt(N)
- N_2 = 0.79±0.0066 (0.8% RMS)
- O_2 = 0.21±0.0028 (1.3% RMS)
- Simple 2-point calibration: argon for **Zero**, and dry air for **Span**

Real-Time Measurement of Nitrogen Purging Efficacy



Real-Time Multi-Species Chemical Gas Sensing

Respiration Gas Monitoring Example

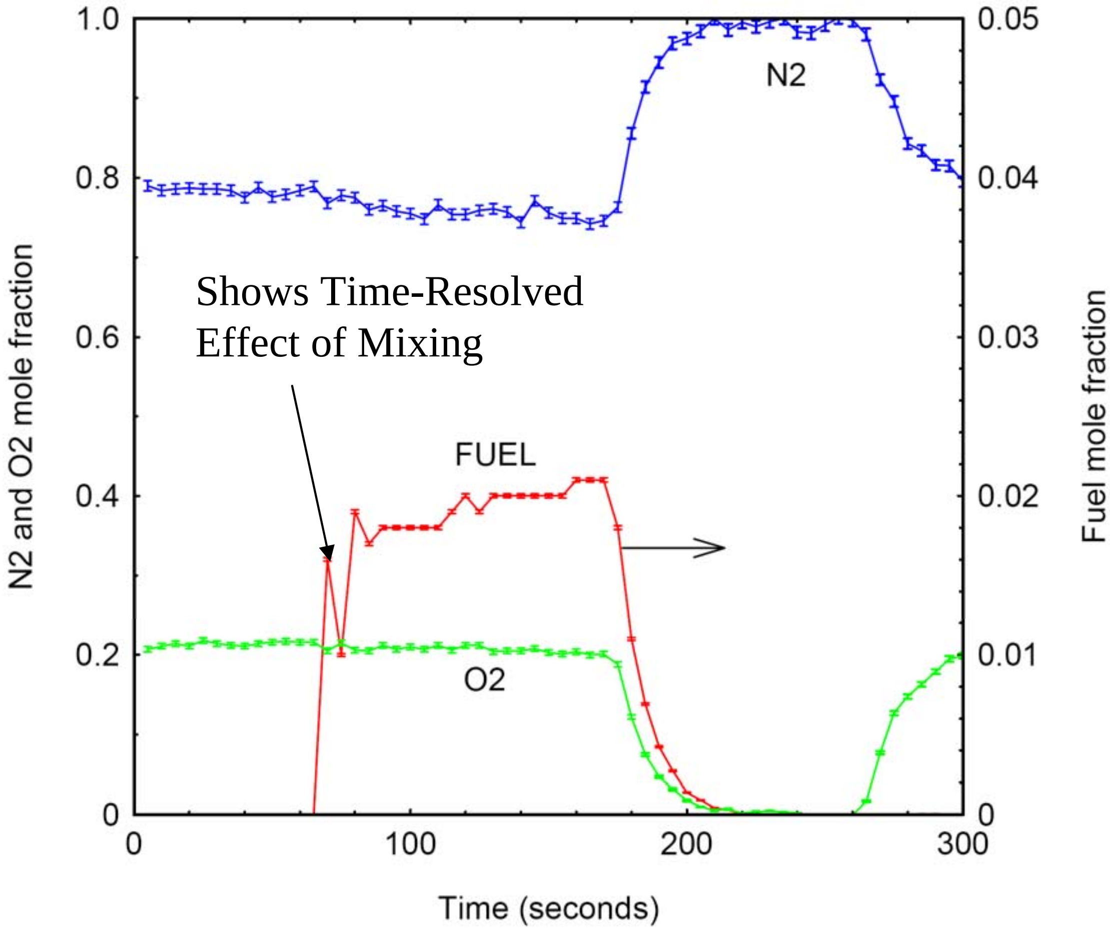


- True multi-species real-time gas sensing system
- Can measure fire suppressants (Halon), and CO_2 for combustion-derived inerting (CDI) applications

- Can be used as a ***false-alarm-free*** fire sensor for inaccessible spaces (via simultaneous detection of CO, CO_2, O_2

Real-Time Measurement of N_2, O_2, and Fuel

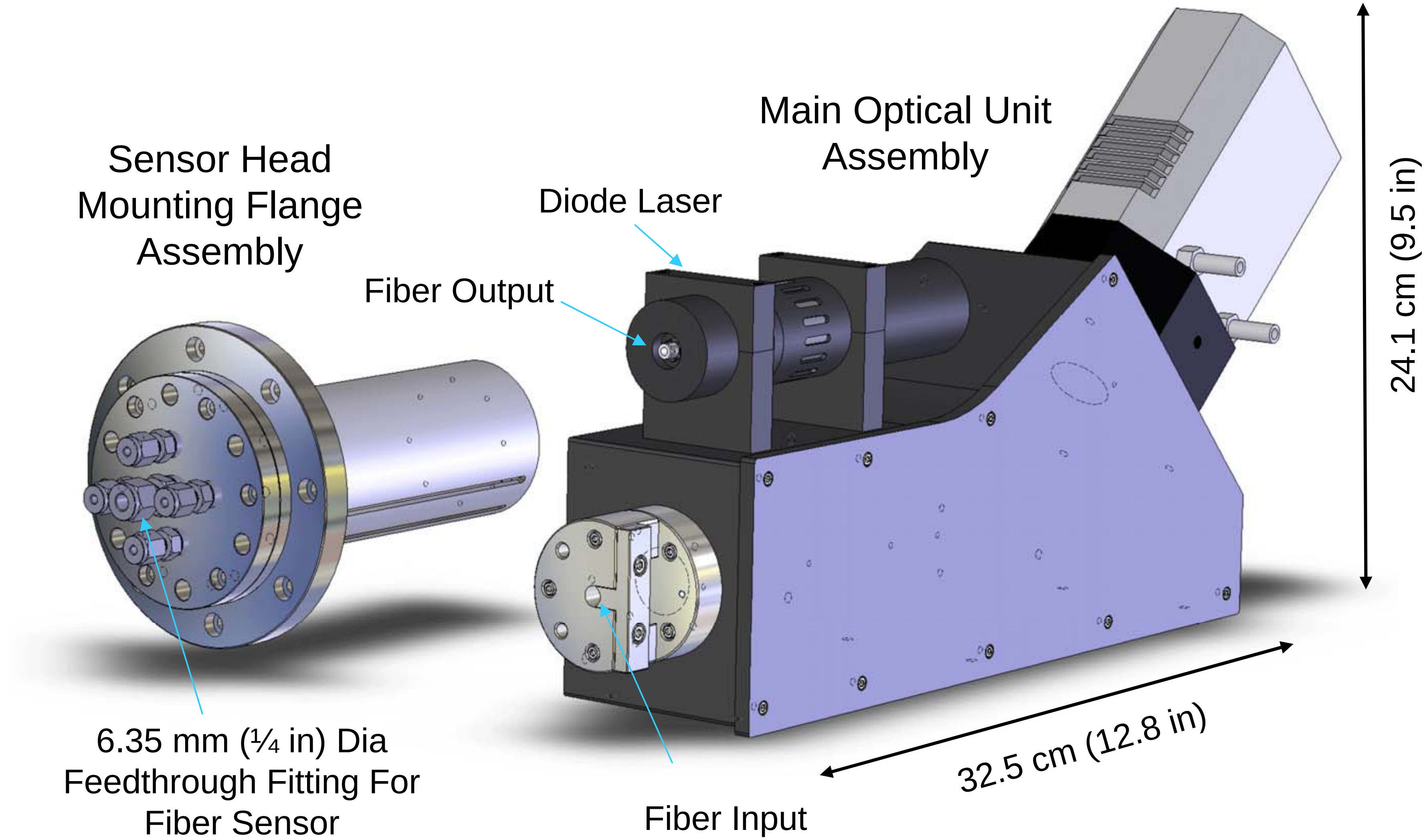
Butane fuel injected into tank initially filled with air, then purged with N_2, then air



- **Fuel & oxygen** provides direct indication of the equivalence ratio
- **Nitrogen & oxygen** measurement gives direct indication of inerting
- Simultaneous measurement of **nitrogen, oxygen & fuel** can provide a physics-based ‘Go/No-Go’ response surface

Q.V. Nguyen (RTB), NASA GRC

CAD Model of Rugged Flight-Capable System



Q.V. Nguyen (RTB), NASA GRC

Review of Features and Advantages

- The NASA-developed fiber optic aircraft fuel tank ullage sensor system is the **ONLY** one that can simultaneously and directly measure nitrogen (N_2), oxygen (O_2), and jet fuel vapor
- **Intrinsically-Safe:** No electrical wiring penetration into fuel tank, low power laser
- **Remote Monitoring:** Fiber optic technique permits remote measurement in harsh environments
- **Real-Time:** Provides rapid indication (5 sec) for safety Go/No-Go, and for OBIGGS feedback control
- **Compact & Low Power:** Small physical dimensions of probe head for easy integration, uses < 30 W power
- **Multi-Species Analysis:** N_2, O_2, CO_2, H_2O, CO, CH_4, other HC's, H_2, Halon, etc.
- **Differentiates** Sat. vs. Un-Sat. HC's
- **Precise:** currently has 1% precision in 5 seconds for N_2; 20 sec gives 0.5%
- **Rugged & Reliable:** system has no moving parts, is alignment-free, no consumables to wear out
- **Cost-Effective:** Monitor multiple locations (tanks) with one optics base unit located in avionics rack; cost-effective when produced in quantities comparable to aircraft
- Can be used for validation and **certification** of other systems

Conclusions

The present fiber optic sensor system provides a comprehensive picture of the real-time fuel tank inerting process and its susceptibility to ignition through a multi-dimensional 'Go/No-Go' response surface that ***increases aircraft operational safety.***

Rather than rely on procedurally-based inerting, the present sensor system enables the use of an OBIGGS feedback control system that reduces bleed air and compressor usage which ***reduces aircraft operational costs.***

Even if conditions in the fuel tank are susceptible to ignition, the comprehensive nature of the information from the present sensor system ***can potentially predict the risk of damage due to pressure rise.***

Work Still Needed

- Build and test flight-hardened system on actual aircraft
- Characterize the Raman spectroscopy of jet fuels and their constituents
- Studies of MIE space for other fuels
- Studies of pressure rise
- Effect of spark shape on ignition and flame propagation
- Effect of fuel composition, humidity, other factors…