

In Situ Multi-Species (O₂, N₂, 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 (N₂), oxygen (O₂), 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 N₂ 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 N₂, (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 CO₂ and CO, and decreased O₂), 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

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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 N₂, O₂, 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?

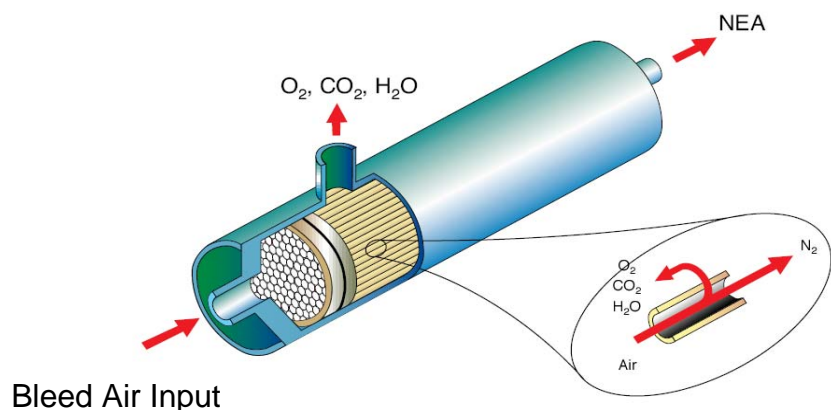


Why Measure N₂, O₂, and Fuel? Cont'd

- Fuel vapor and O₂ concentration provides indicator of the *inherent chemically-based susceptibility to ignition* (kinetics)
- N₂ concentration provides indicator of *inherent ability of inerting compound to absorb heat in event of ignition* (thermicity)
- Direct measurement of N₂ 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 N₂/O₂/Fuel provides comprehensive picture to make informed decisions that **increases aircraft safety**
- Almost ALL current fuel tank ullage sensors only measure oxygen (O₂)



ASM's Produce Nitrogen Enriched Air (NEA)



NASA/CR 2001-210950 by Reynolds et al.

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

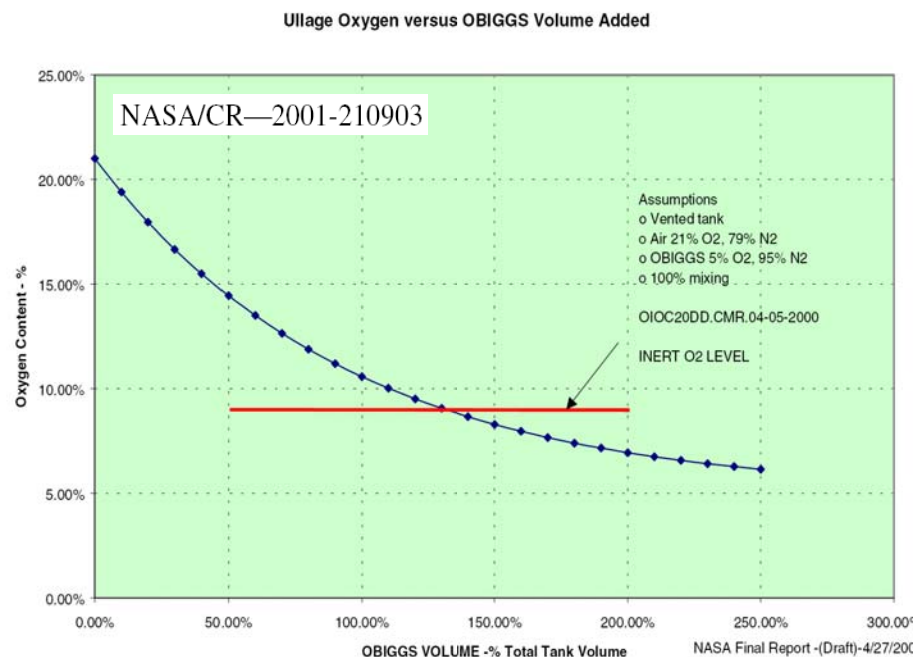


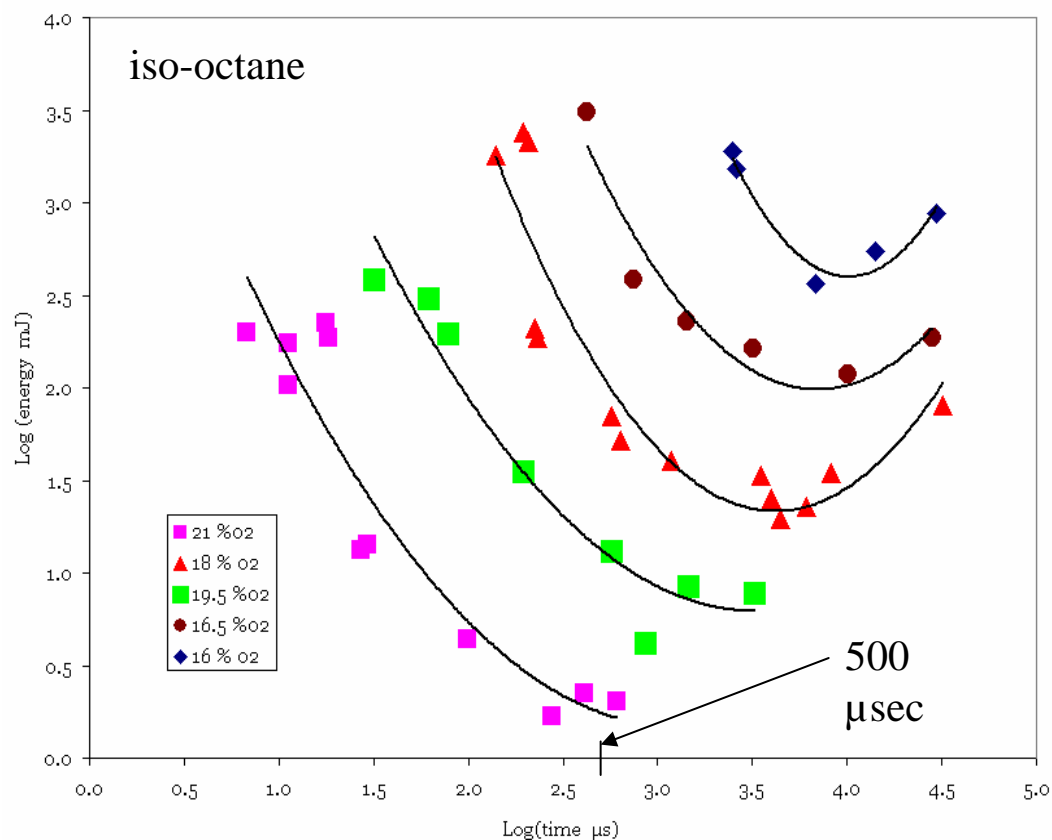
Figure 5.0-36. Ullage Oxygen Versus OBIGGS Volume Added

Is measuring O₂ alone the best way to predict safety, and provide feedback control of OBIGGS for N₂ generation?



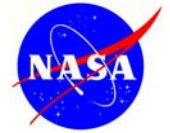
Fuel Ignition Studies at GRC

Effect of Spark Duration and Oxygen on Minimum Ignition Energy (MIE) at 14.5 C⁰

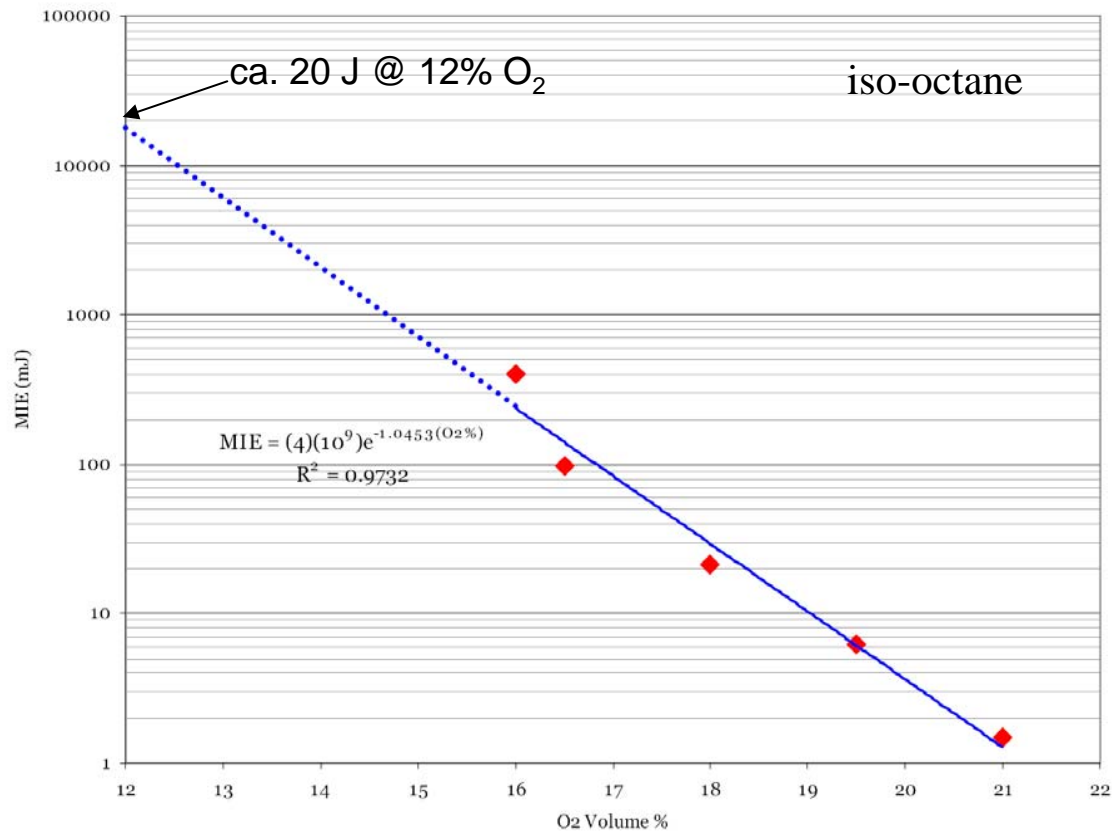


Data, courtesy M.J. Rabinowitz (RTB), NASA GRC

Fuel Ignition Studies at GRC



Effect of O₂ on MIE at 14.5 C⁰

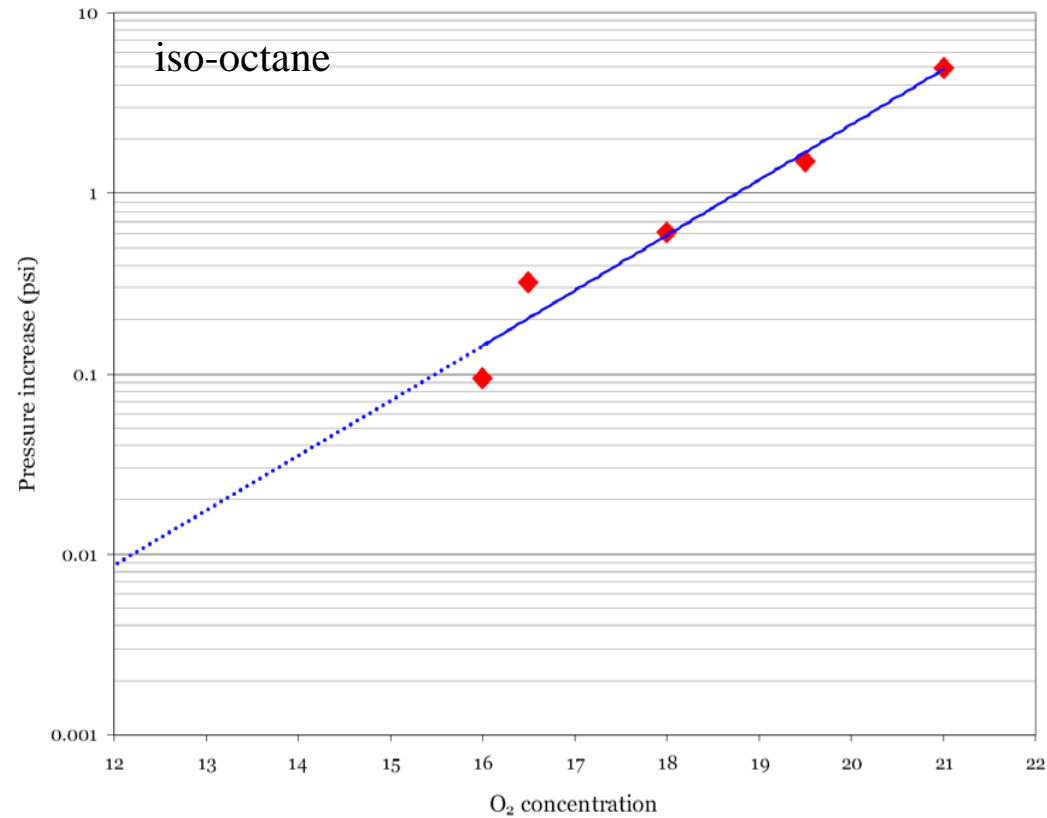


Data, courtesy M.J. Rabinowitz (RTB), NASA GRC

Fuel Ignition Studies at GRC



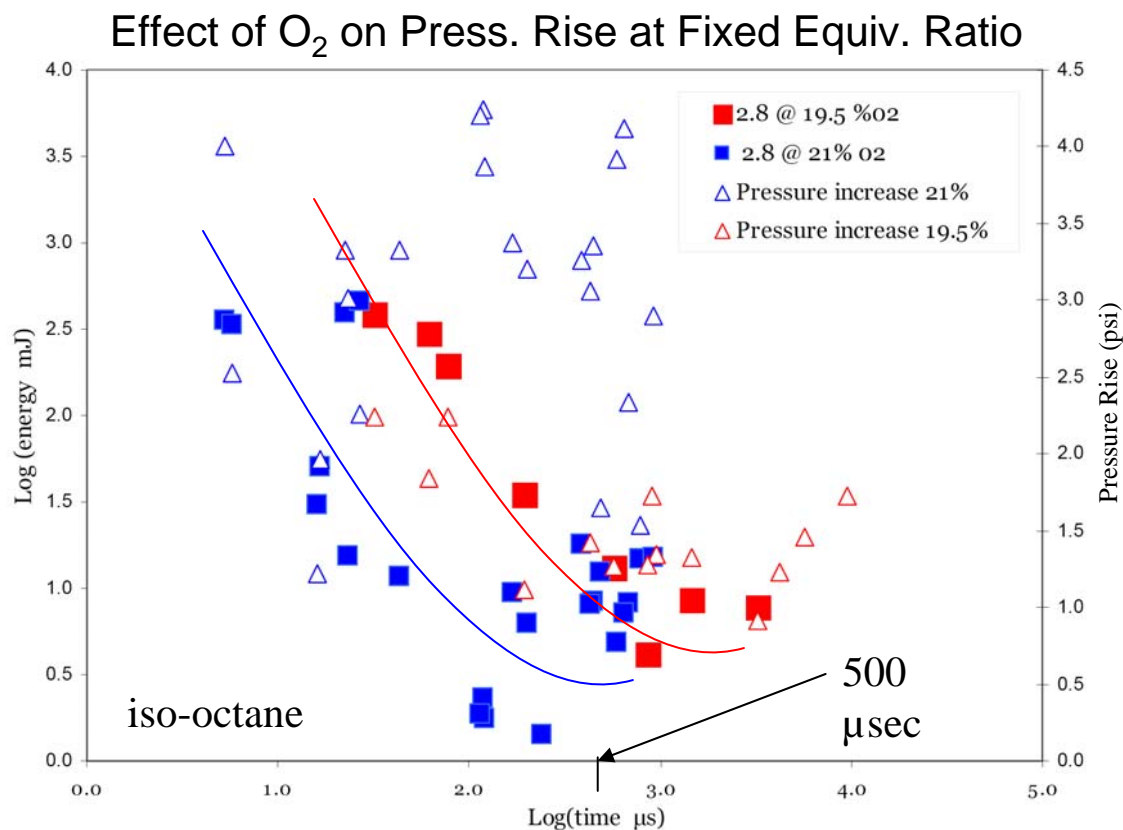
Effect of O₂ on Pressure Rise at 14.5 C⁰



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



Fuel Ignition Studies at GRC



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

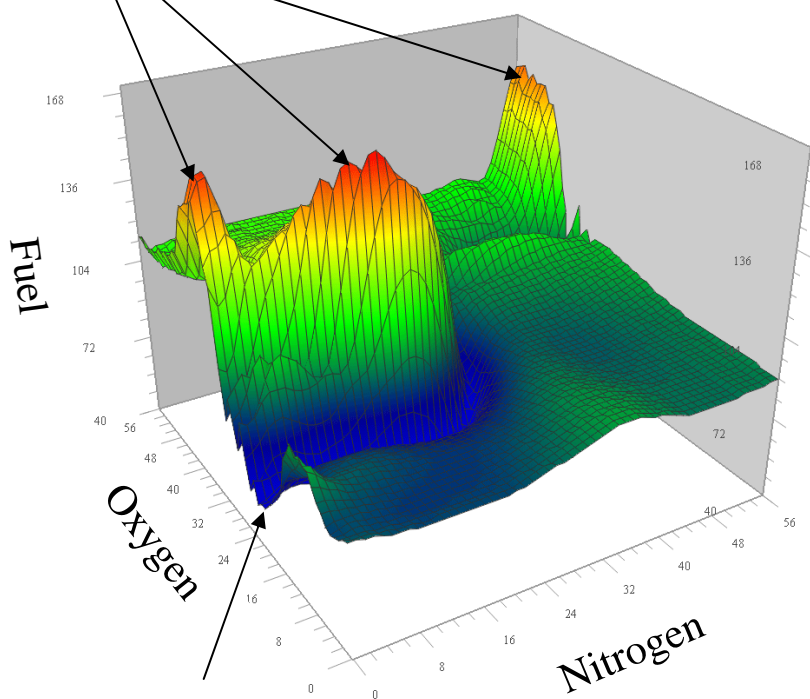
Need a physics-based 'Go/No-Go' decisional response surface



Multi-Dimensional Response Surface

Notional Example of a Response Surface

Dangerous Regions



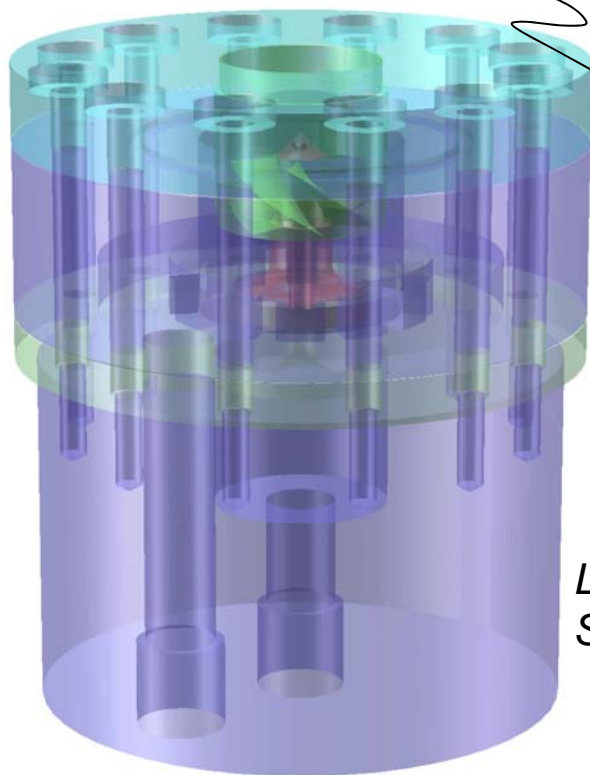
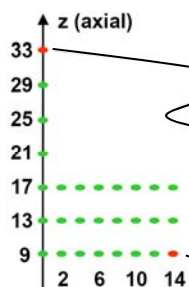
Safe Regions

Inputs:

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

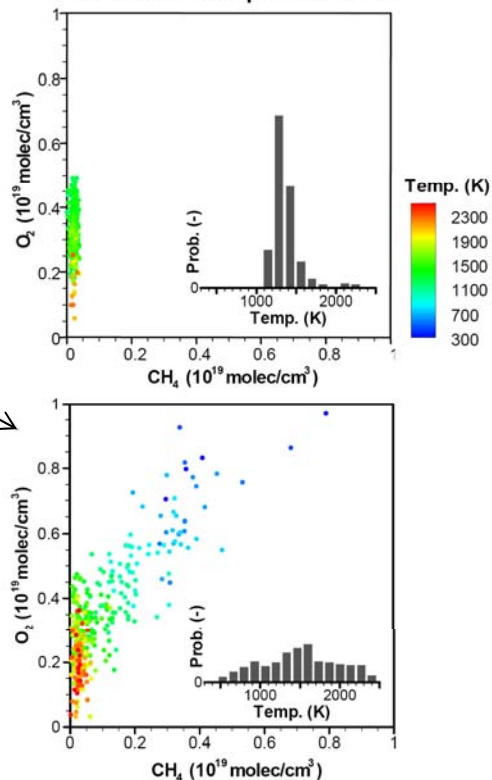
Genesis – Laser Diagnostics in Turbulent Flames

5-atm CH₄-Air Flame



*Lean Direct Injection (LDI)
Swirl Stabilized Burner*

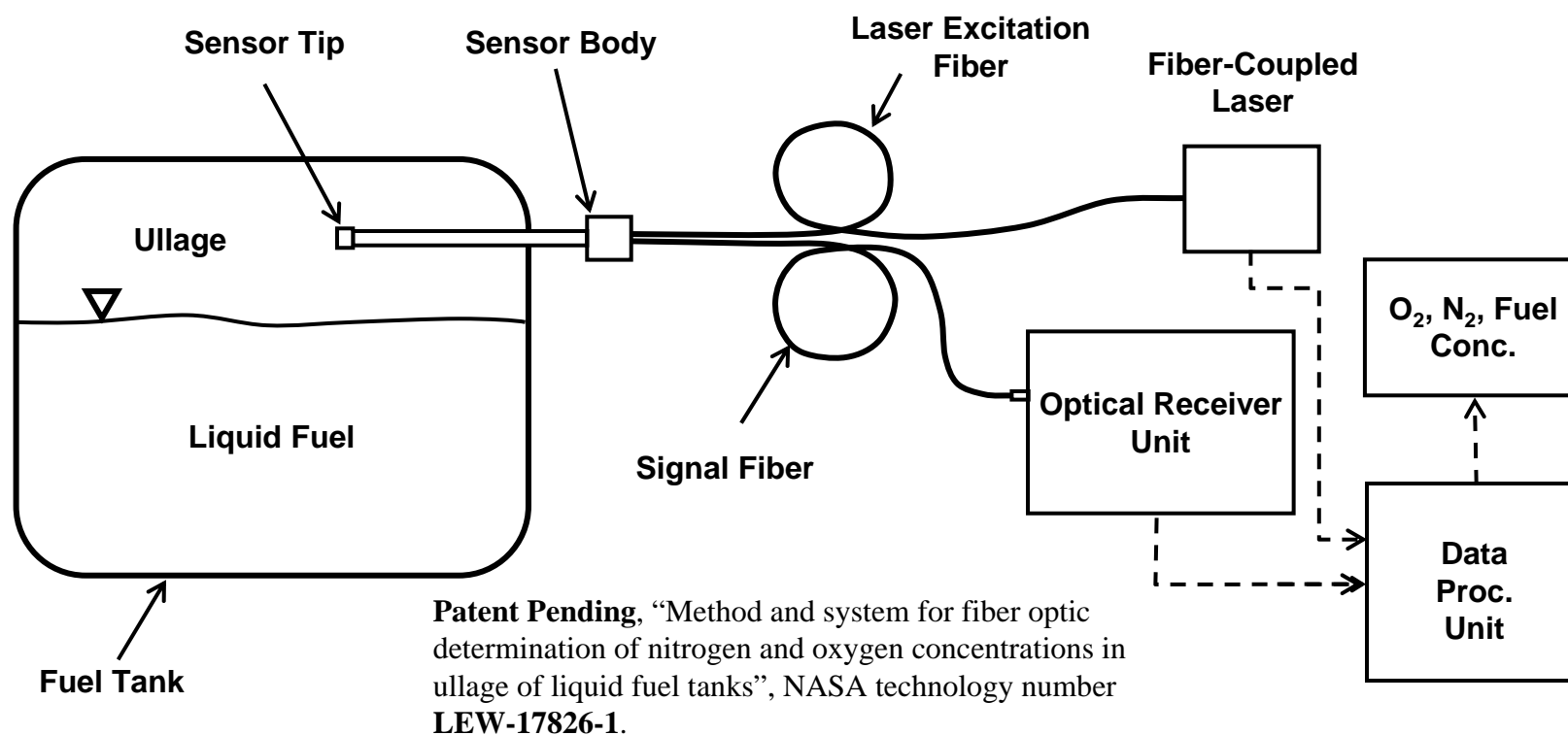
Fuel-Oxidizer-Temp Scatter Plots



- 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?***

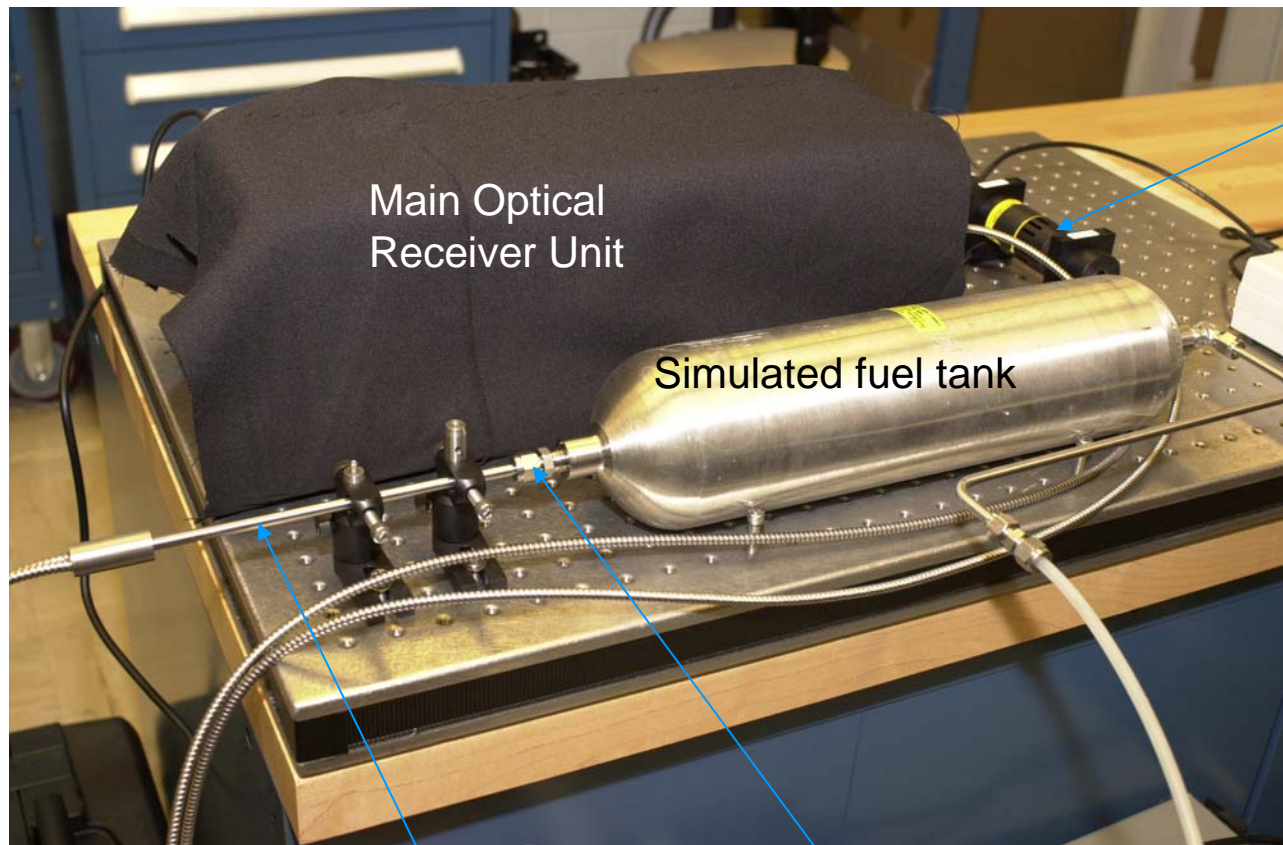


Fiber Optic Sensor System for Fuel Tank Ullage



- **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 to 15 μ J in 500 μ s*)
- **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



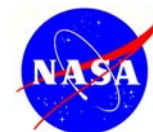
Excitation
Diode
Laser

Main Optical
Receiver Unit

Simulated fuel tank

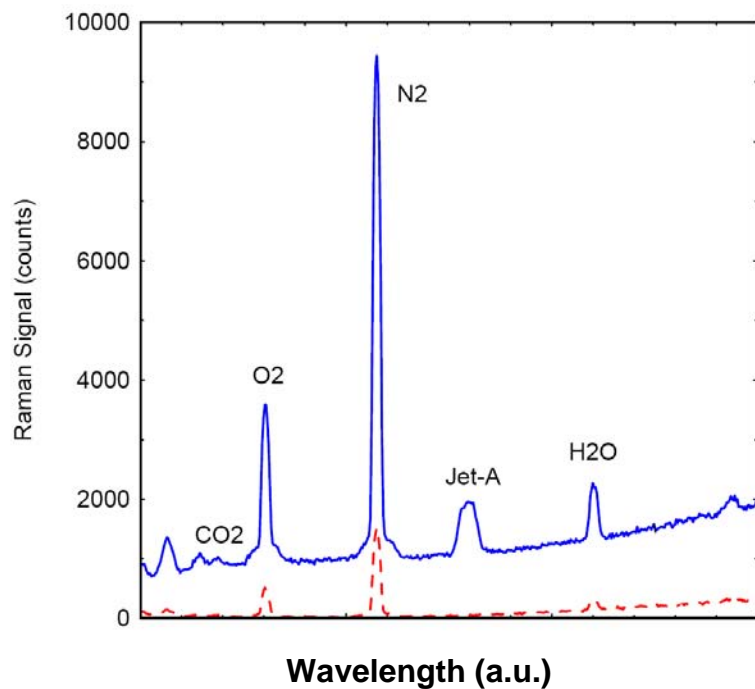
1/4 in Dia.
Stainless Steel
Probe Tip

Simple
Feedthrough
Fitting

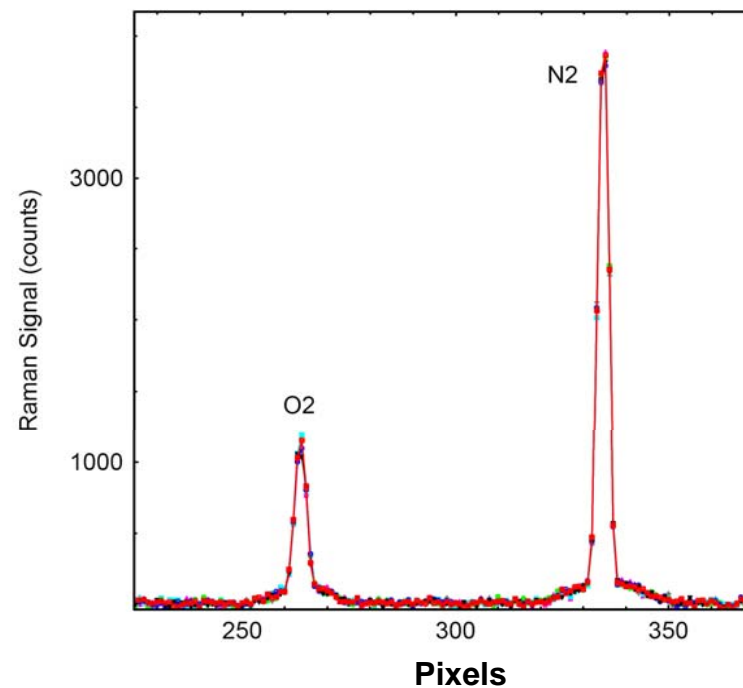


Raman Scattering of Various Gases

20 sec acq. with 30 mW laser



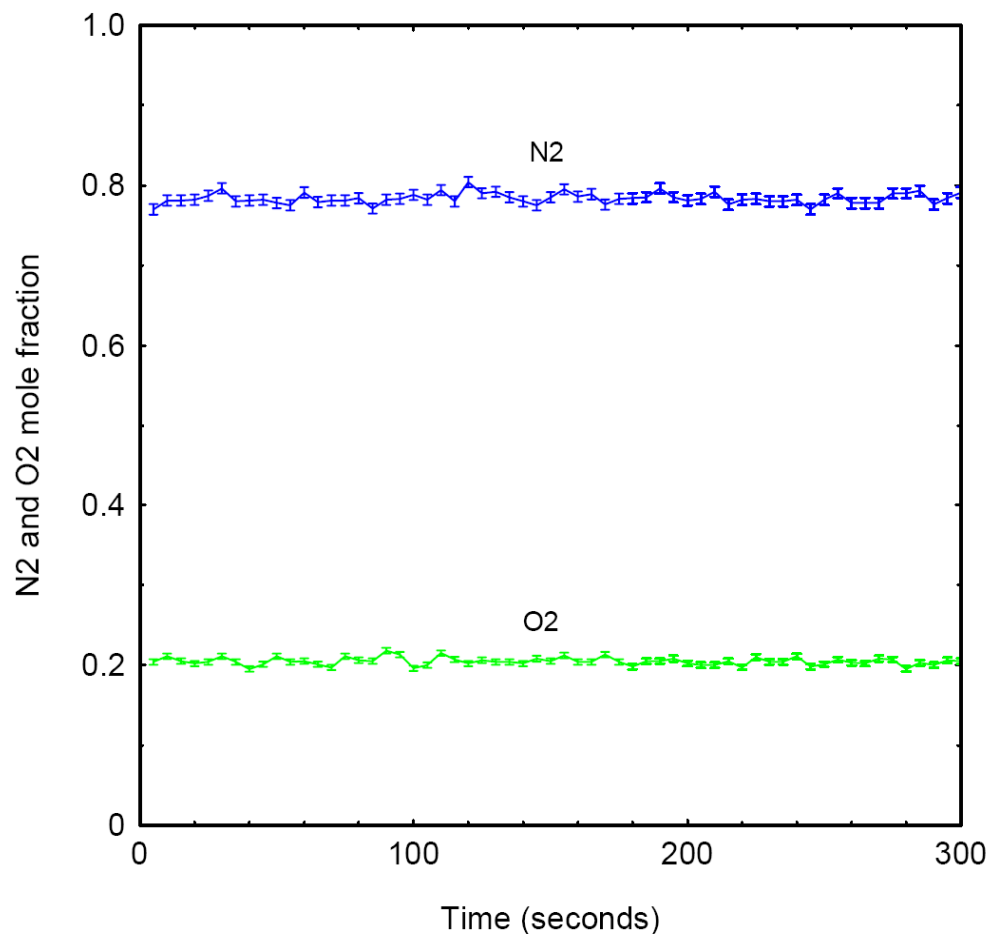
8 different spectra superimposed



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

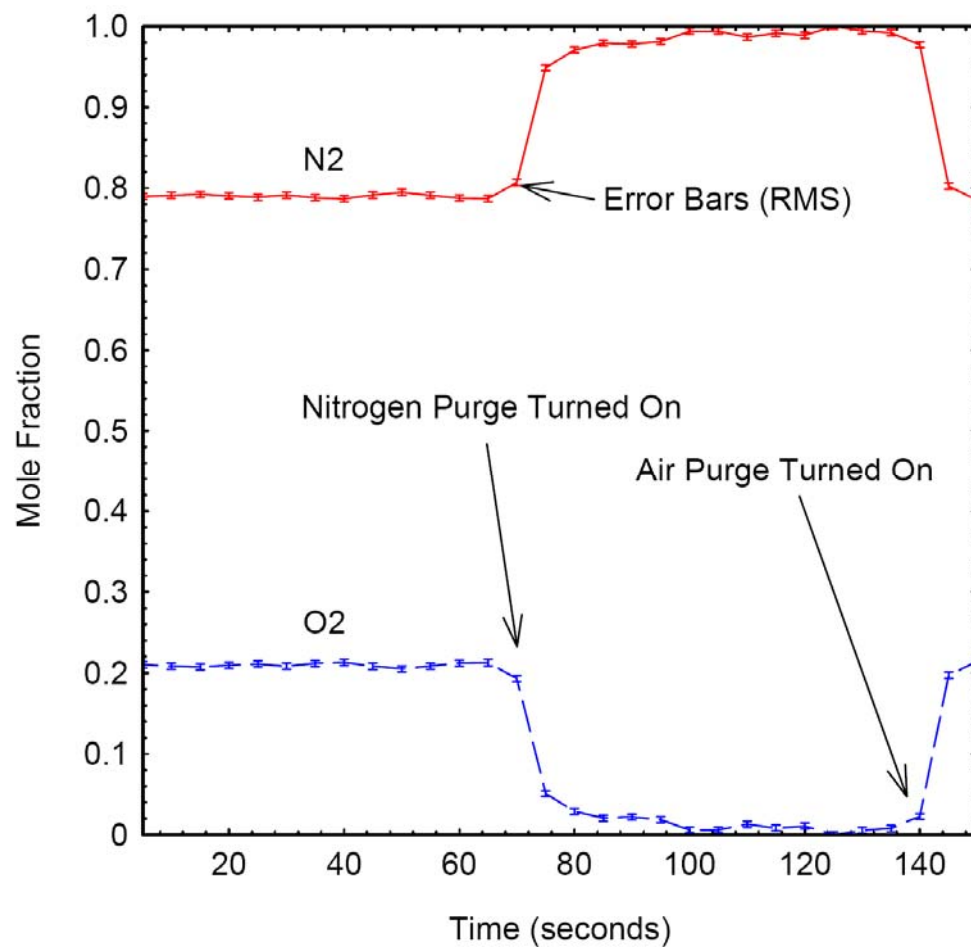


Measurement Stability in Ambient Air



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

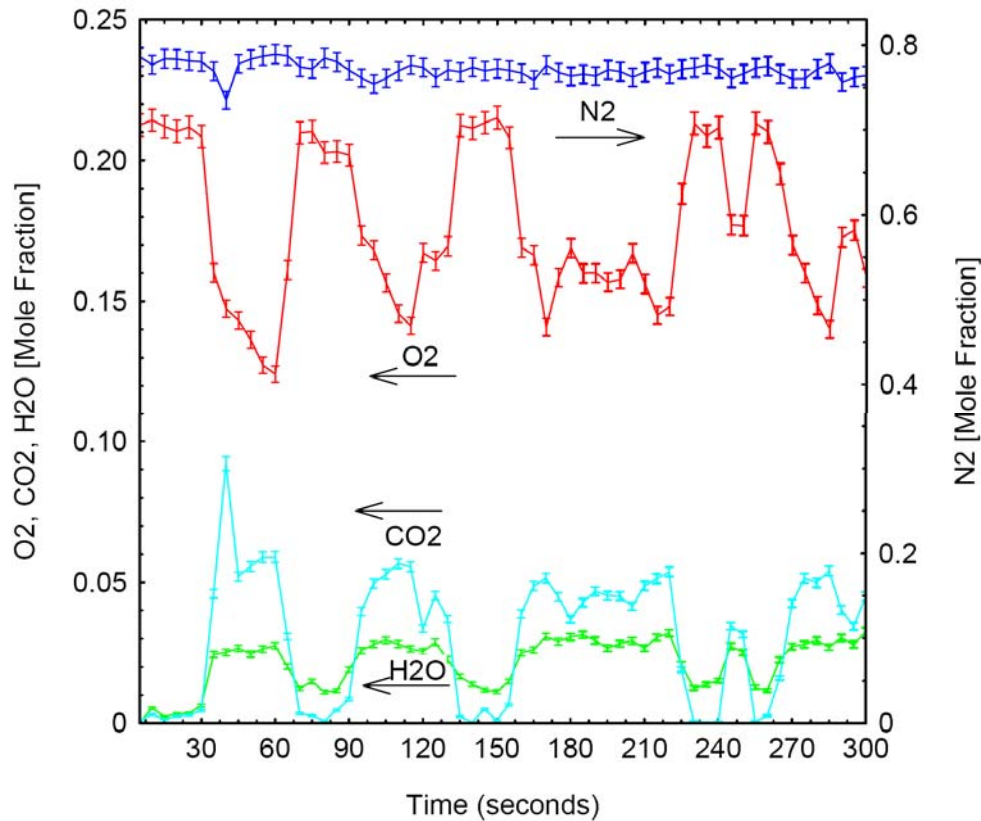
Real-Time Measurement of Nitrogen Purging Efficacy



Real-Time Multi-Species Chemical Gas Sensing



Respiration Gas Monitoring Example



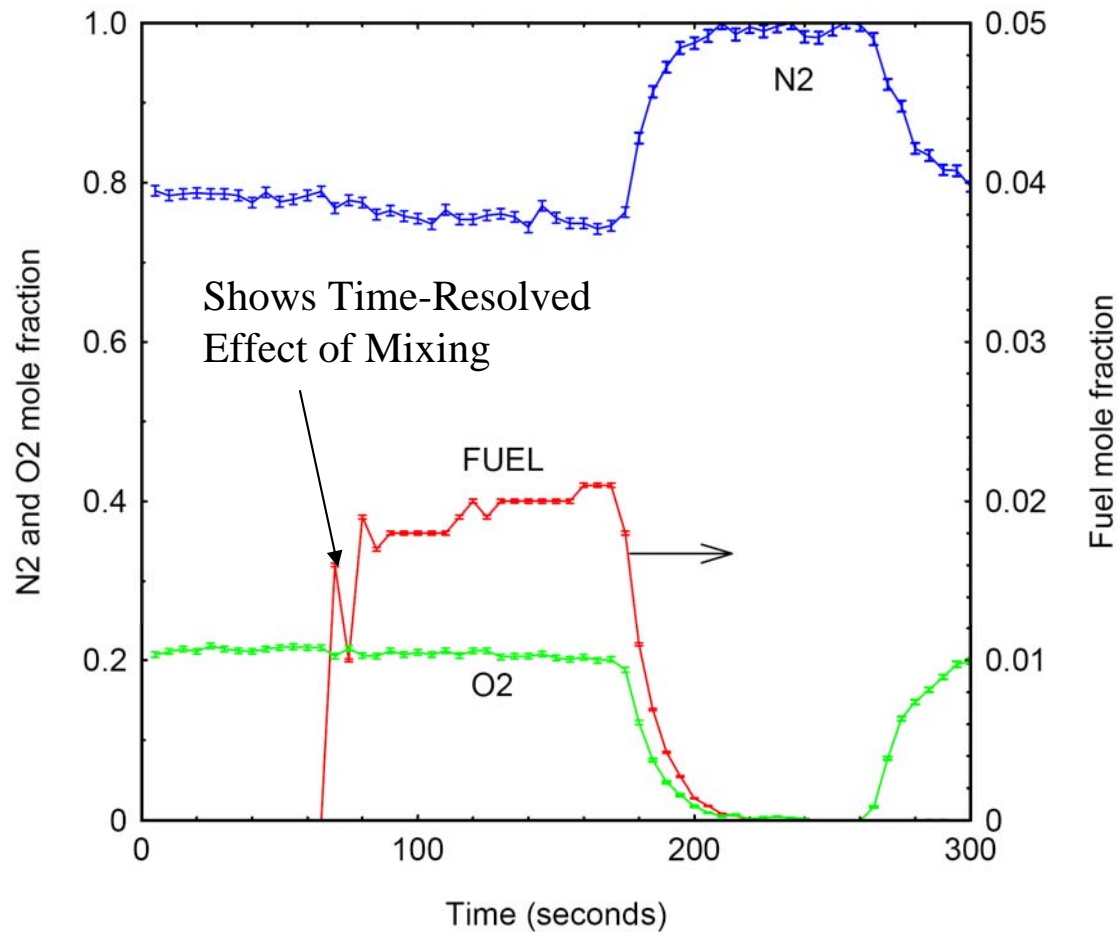
- True multi-species real-time gas sensing system
- Can measure fire suppressants (Halon), and CO₂ for combustion-derived inerting (CDI) applications

• Can be used as a **false-alarm-free** fire sensor for inaccessible spaces (via simultaneous detection of CO, CO₂, O₂)

Real-Time Measurement of N₂, O₂, and Fuel

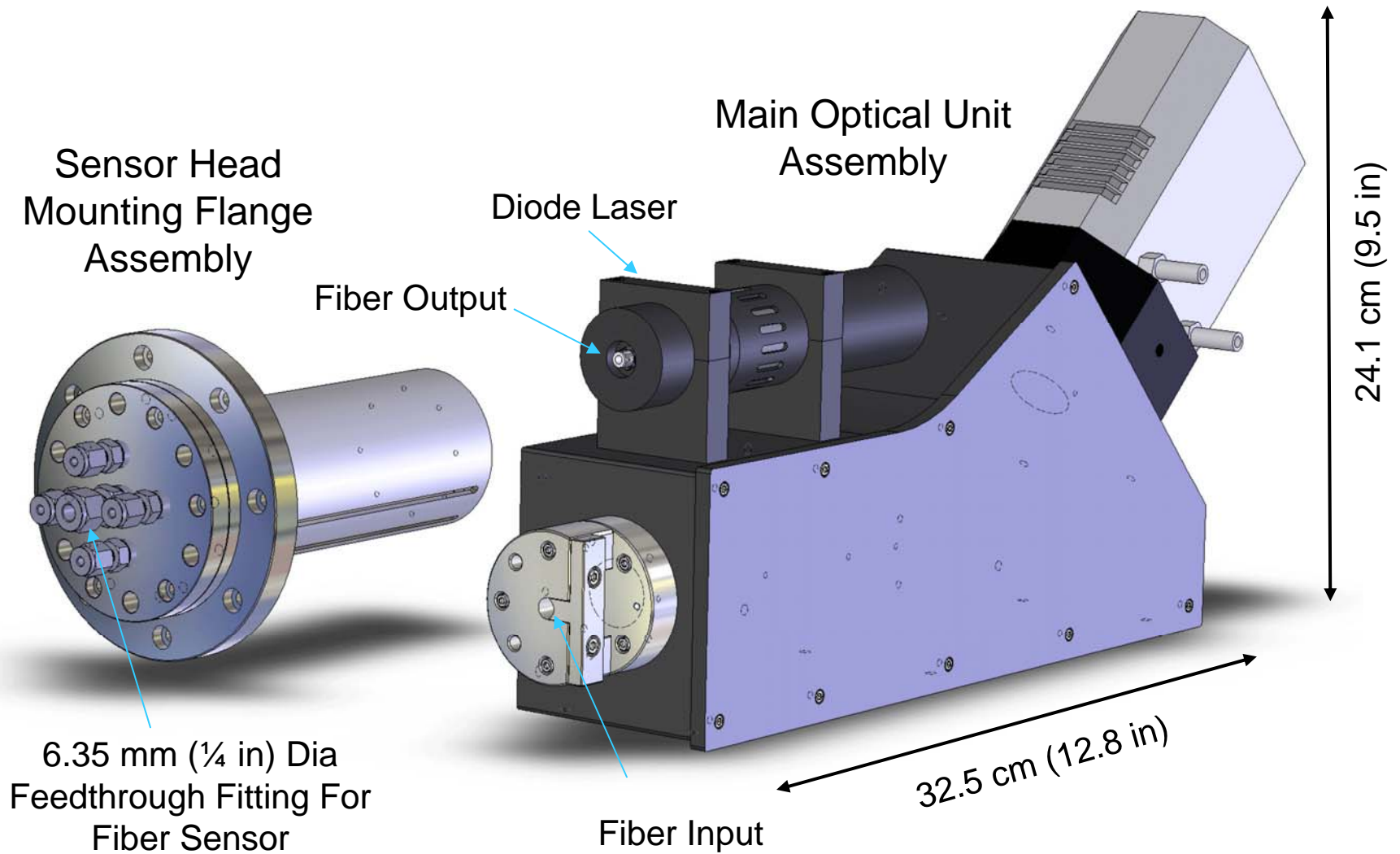
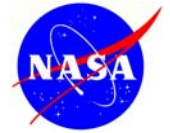


Butane fuel injected into tank initially filled with air, then purged with N₂, then air

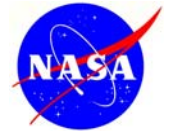


- **Fuel & oxygen** provides direct indication of the equivalence ratio
- **Nitrogen & oxygen** measurement gives direct indication of inerting
- Simultaneous measurement of **nitrogen, oxygen & fuel** can provide a physics-based 'Go/No-Go' response surface

CAD Model of Rugged Flight-Capable System



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...