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 N_2, O_2, and Fuel?

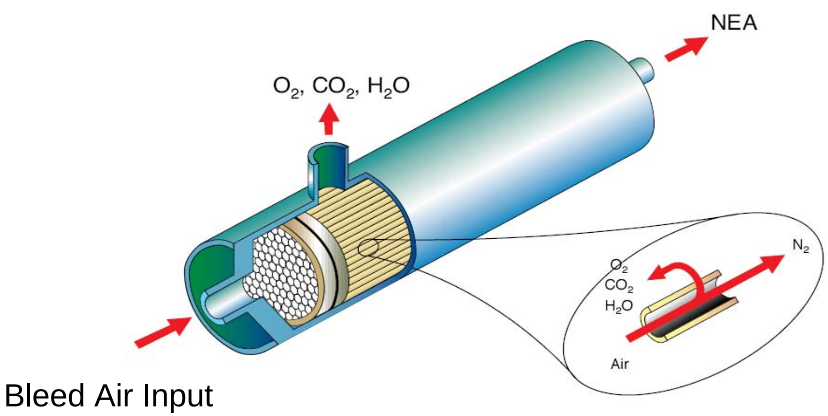
- Absolute risk of ignition is always there – cannot be zero
- How much inerting is required for a reasonable level of safety?
- Measurement of Oxygen, Nitrogen, and Fuel Vapor *(volatiles vs. non-volatiles)* gives more accurate indication of Minimum Ignition Energy (MIE)
- The more information available, 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.

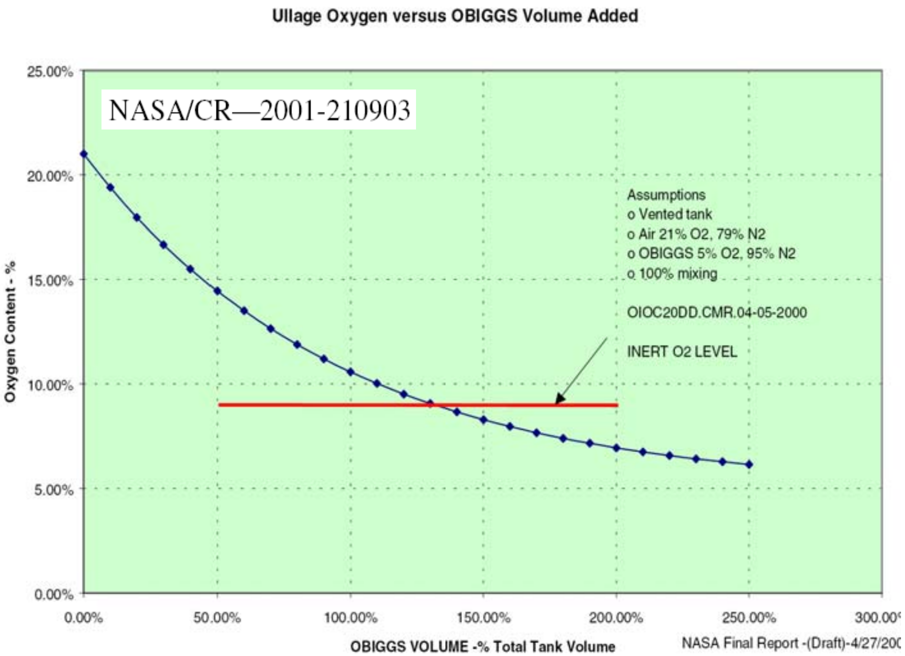


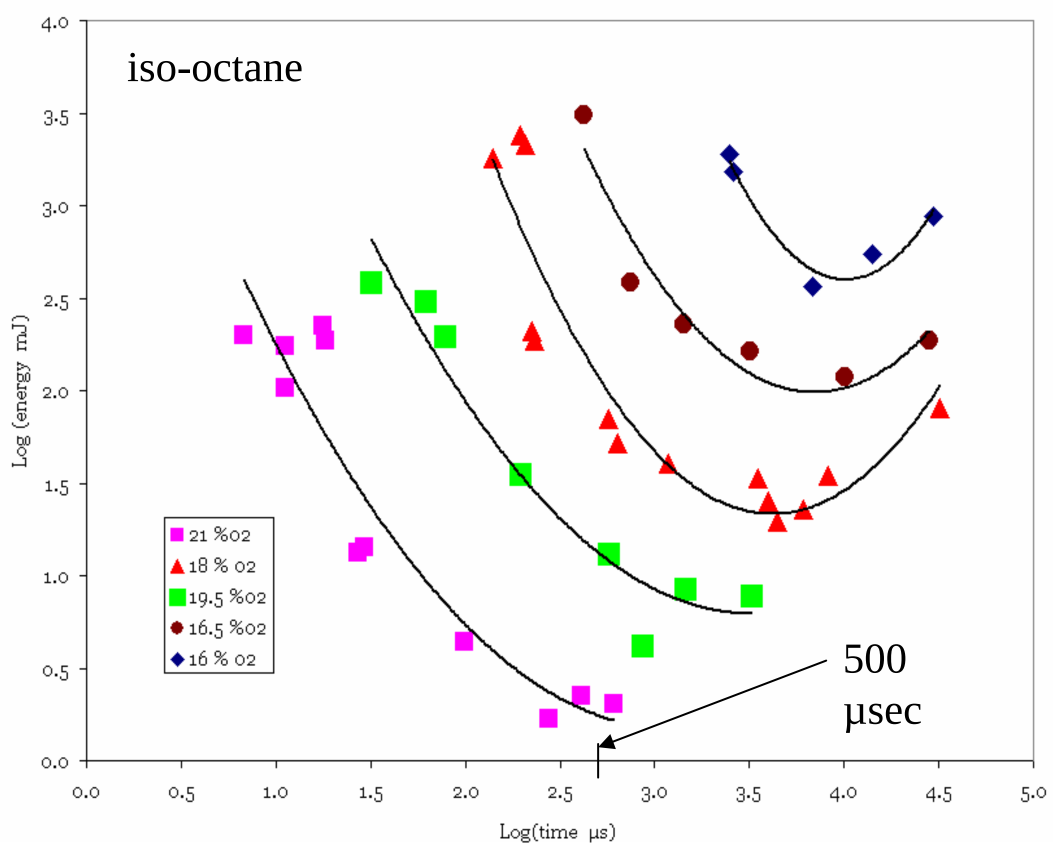
Figure 5.0-36. Ullage Oxygen Versus OBIGGS Volume Added

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

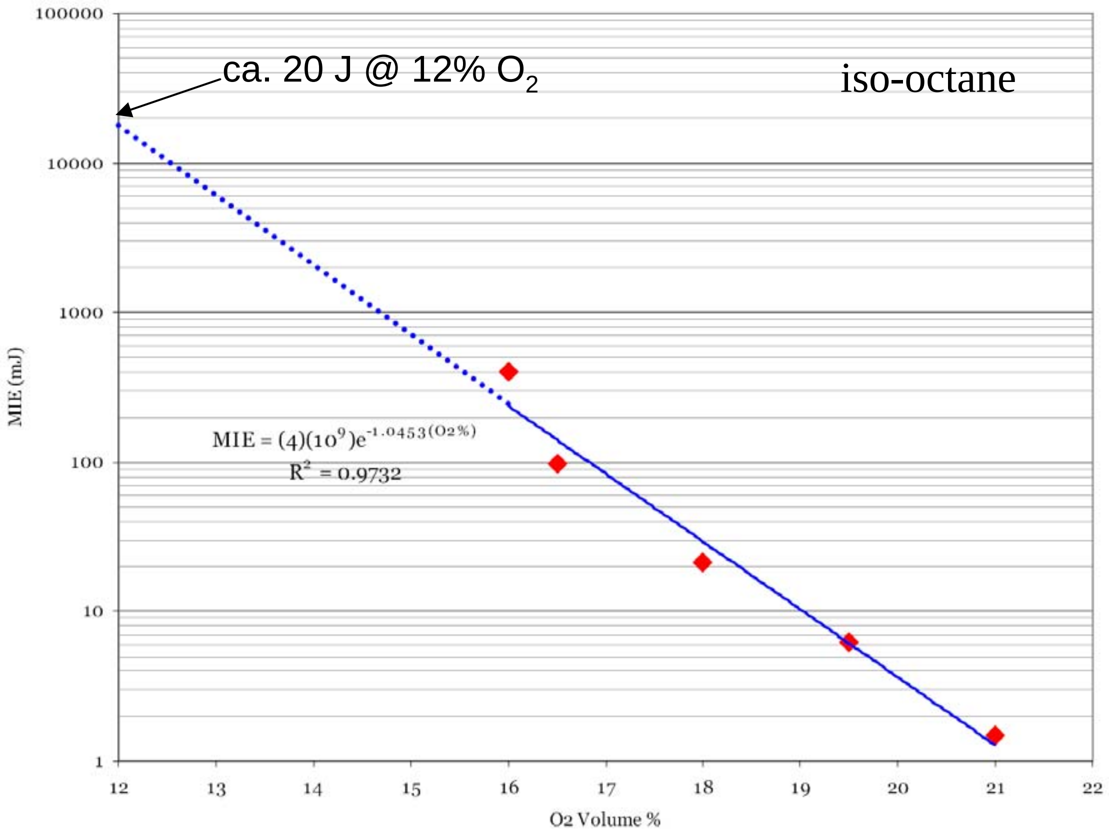


Data, courtesy M.J. Rabinowitz (RTB), NASA GRC

Q.V. Nguyen (RTB), NASA GRC

Fuel Ignition Studies at GRC

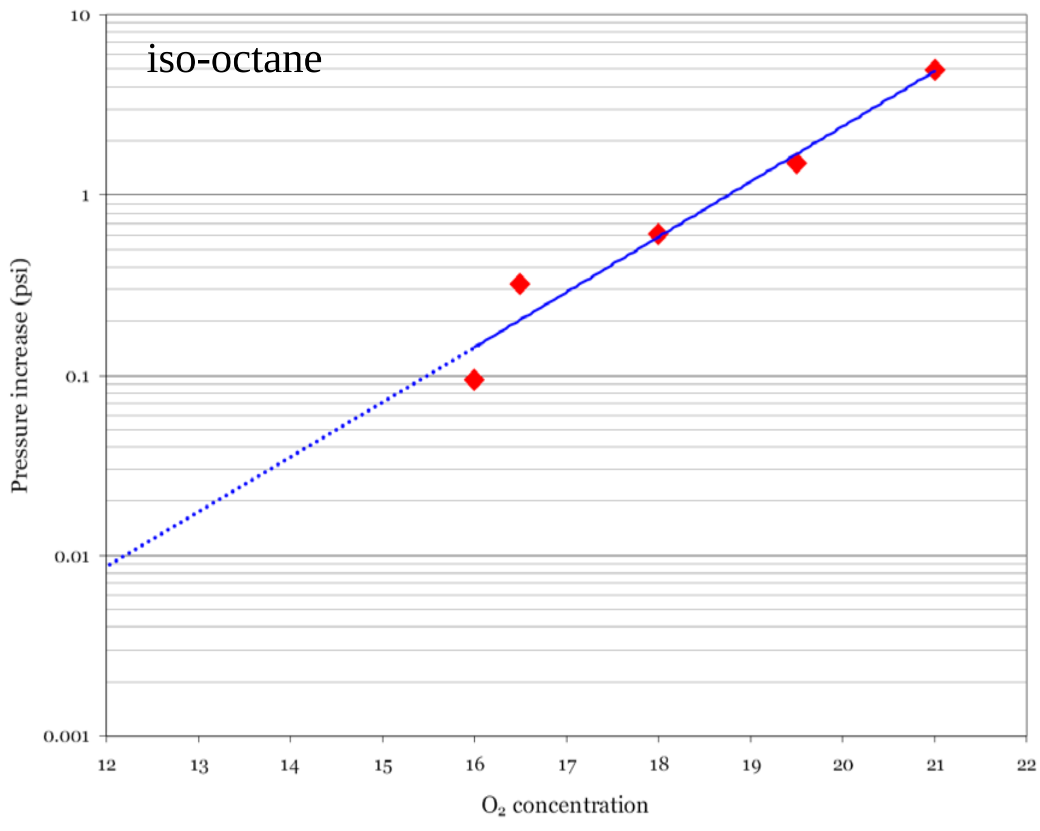
Effect of O_2 on MIE at 14.5 C^0



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

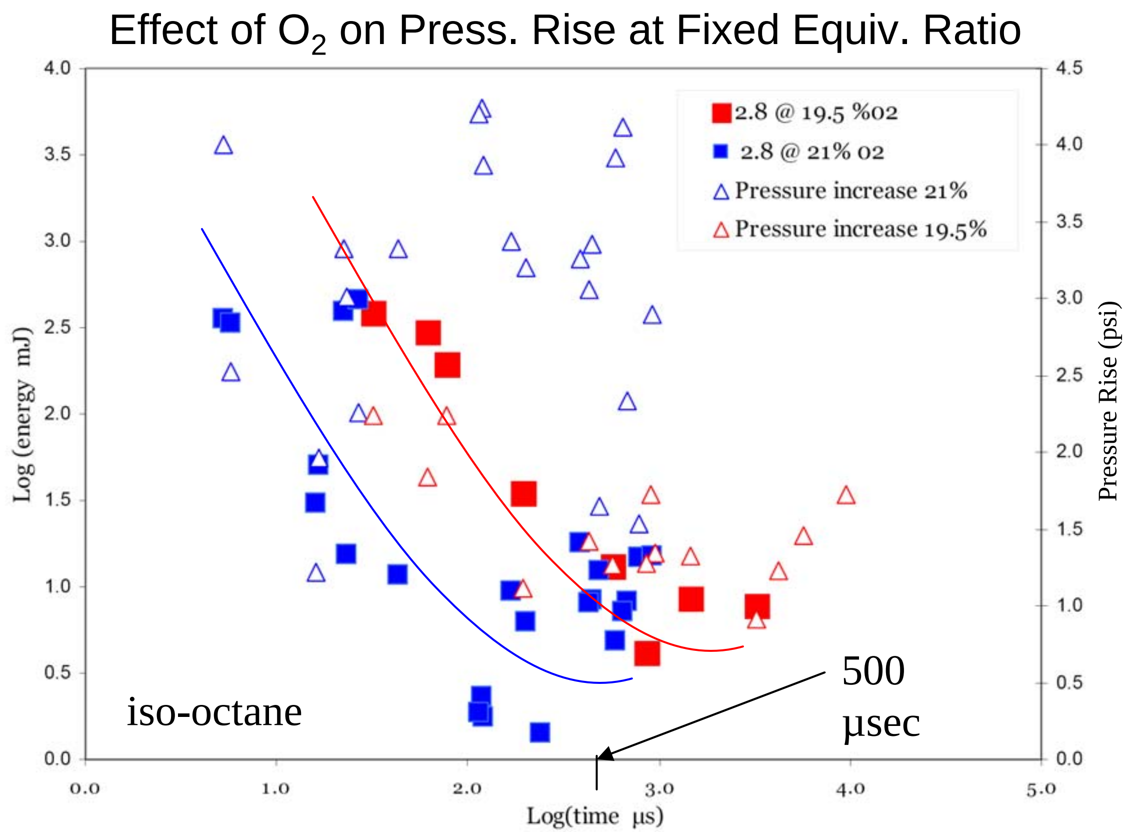
Fuel Ignition Studies at GRC

Effect of O_2 on Pressure Rise at 14.5 C^0



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

Fuel Ignition Studies at GRC

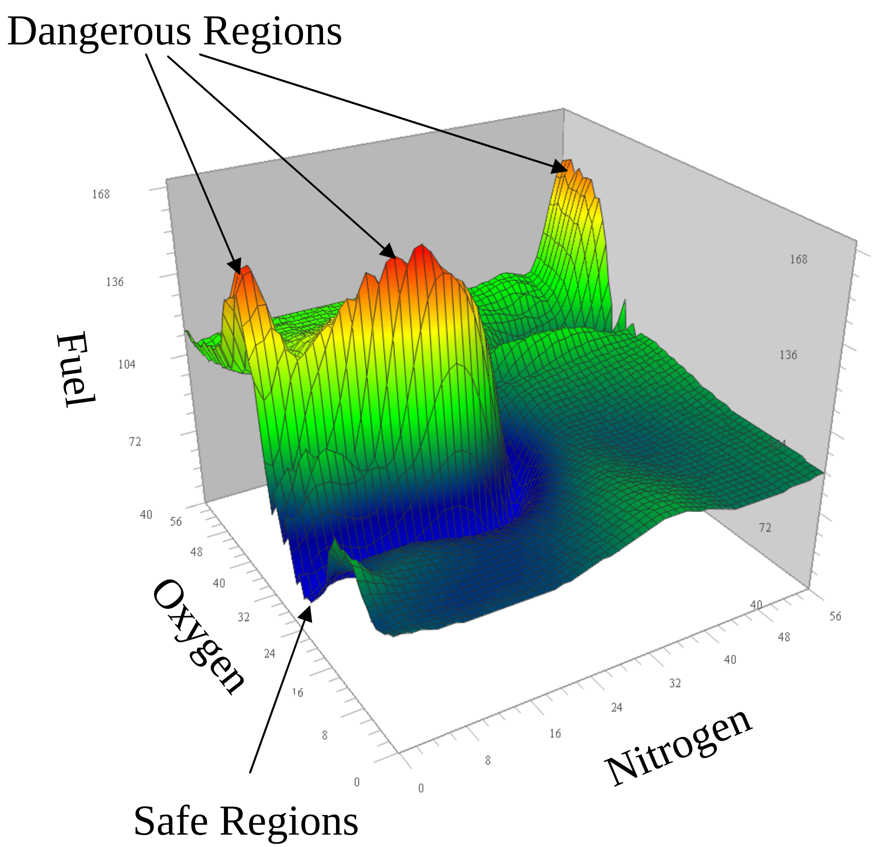


Data, courtesy M.J. Rabinowitz (RTB), NASA GRC

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

Multi-Dimensional Response Surface

Notional Example of a Response Surface



Inputs:

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

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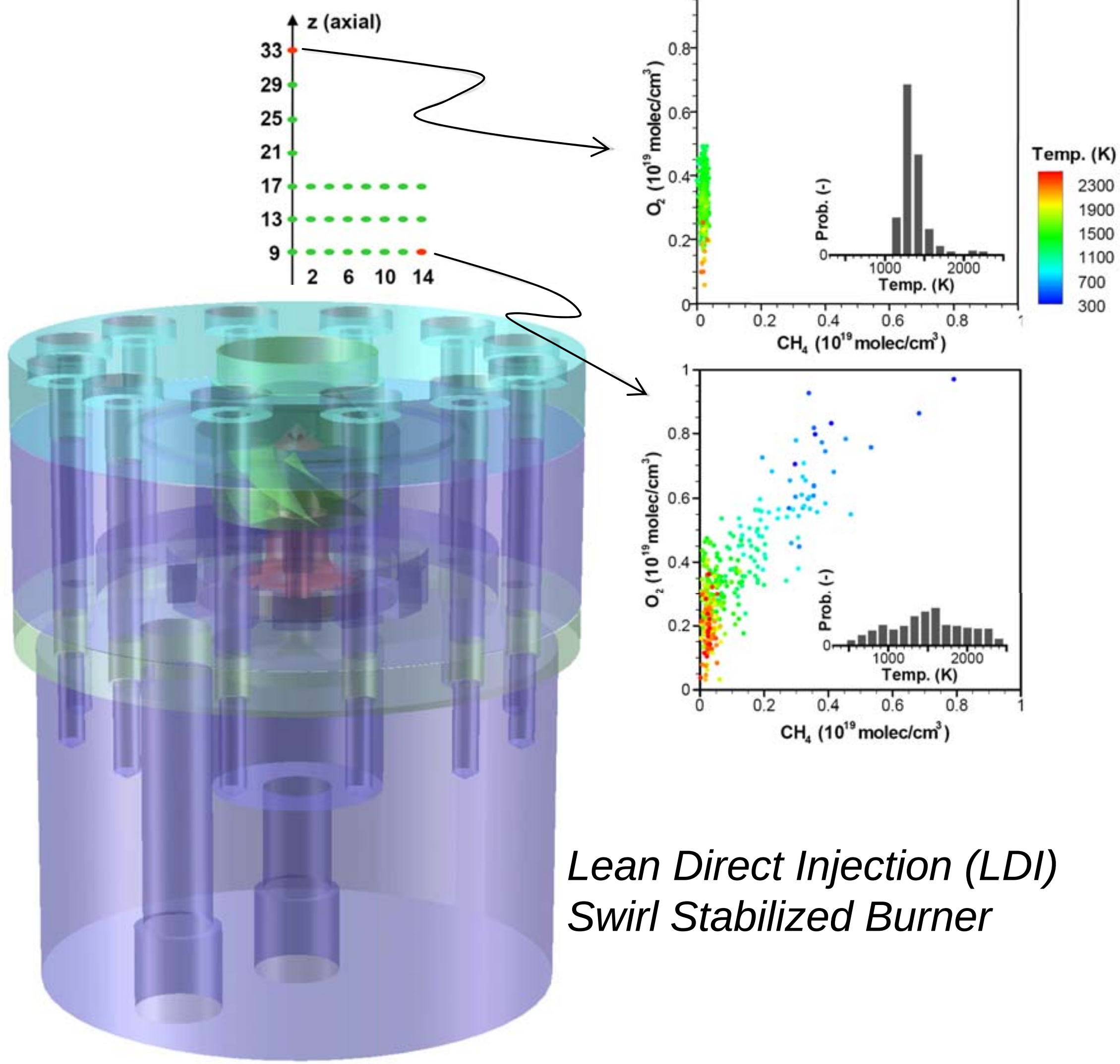
Genesis – Laser Diagnostics in Turbulent Flames

5-atm CH_4-Air Flame

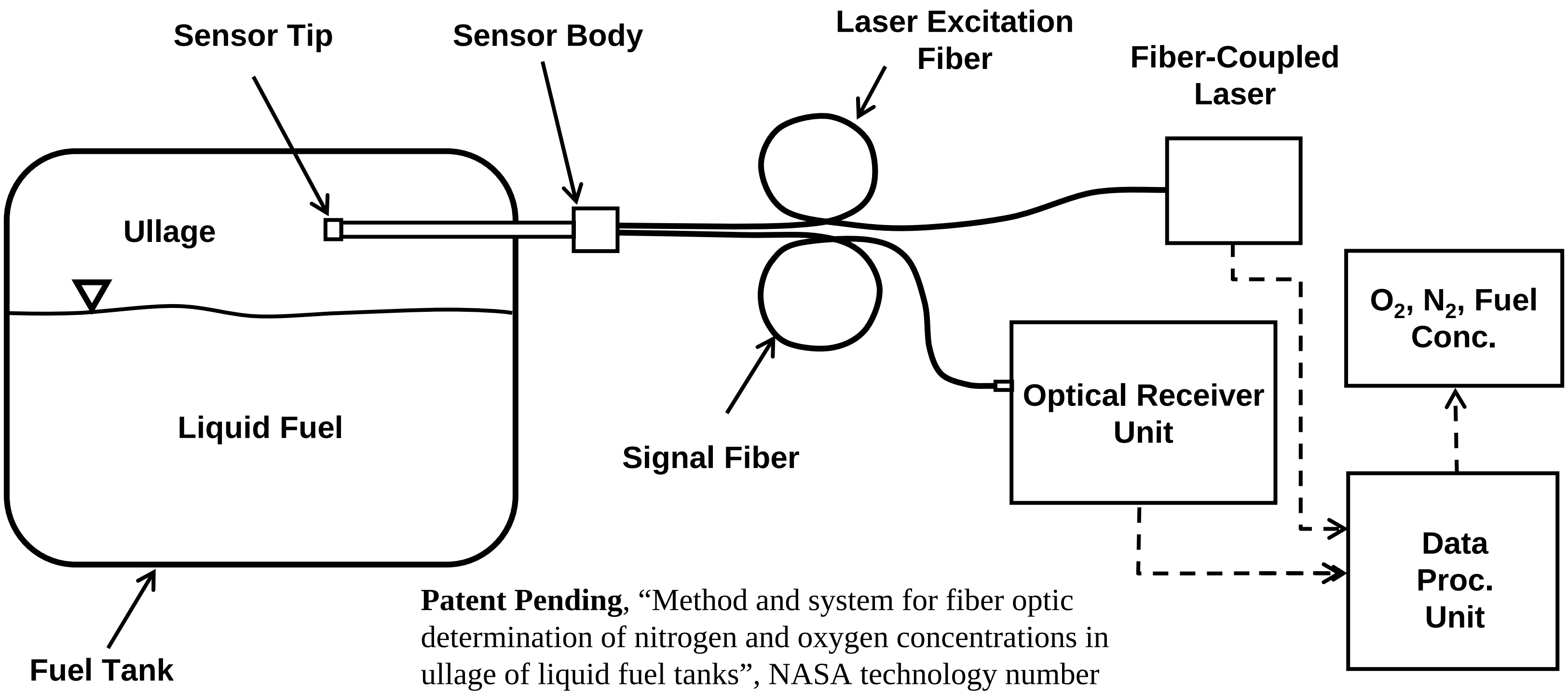


Lean Direct Injection (LDI)
Swirl Stabilized Burner

- 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

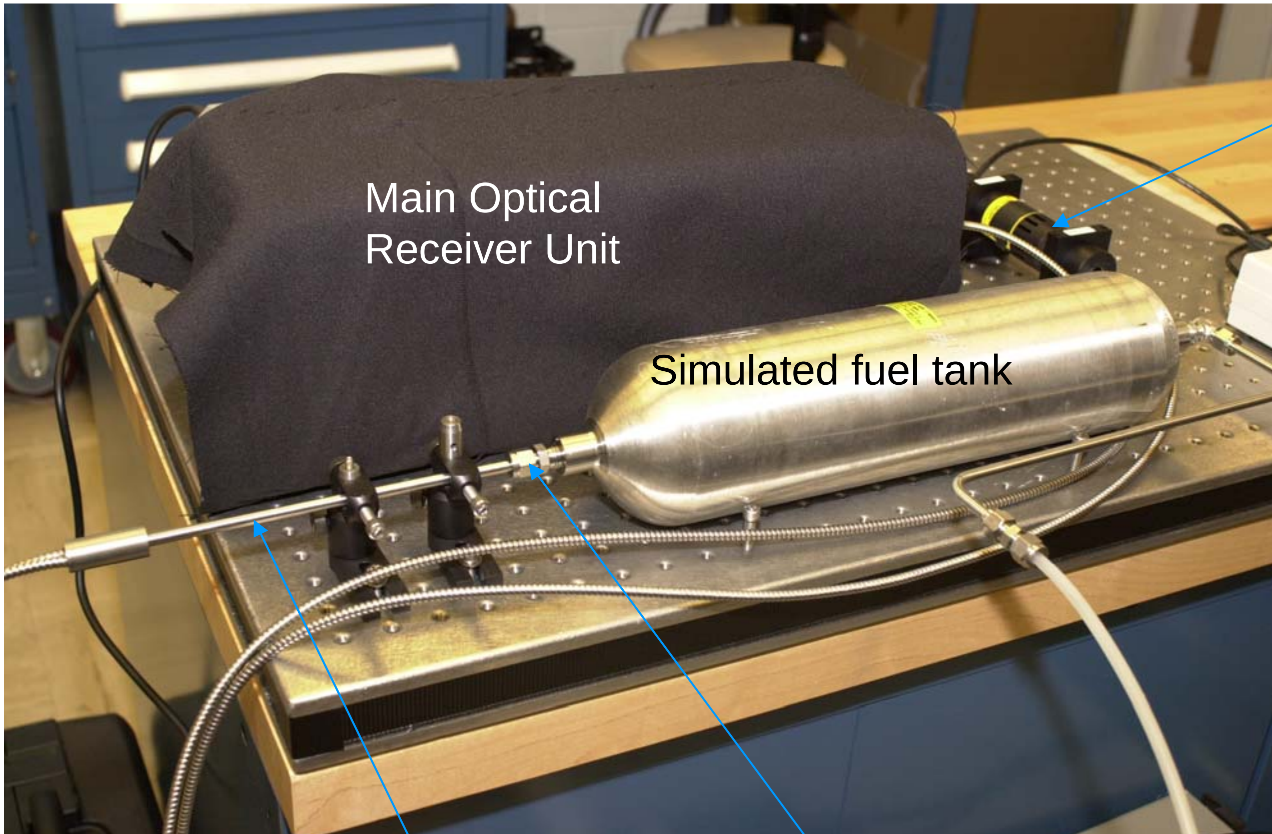
Fiber Optic Sensor System for Fuel Tank Ullage



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**.

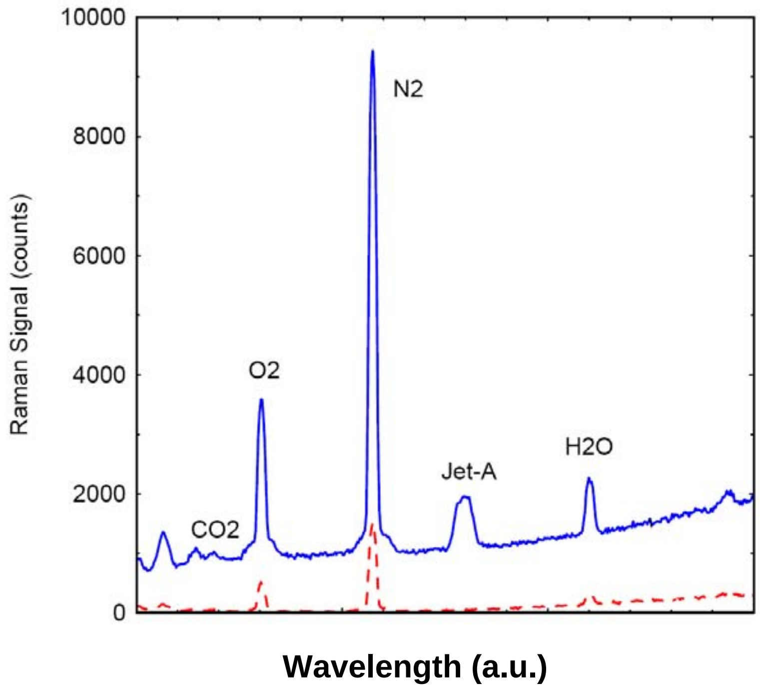
- **Fiber Optic Probe Head:** compact and rugged design fits into tight spaces
- **Laser excitation system:** low-power 30 mW diode laser does not pose ignition danger *(equivalent to15 µJ in 500 µs)*
- **Optical Receiver Unit:** remotely located to avoid harsh environment near fuel tank, permits easy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

Breadboard Fiber Optic Sensor System

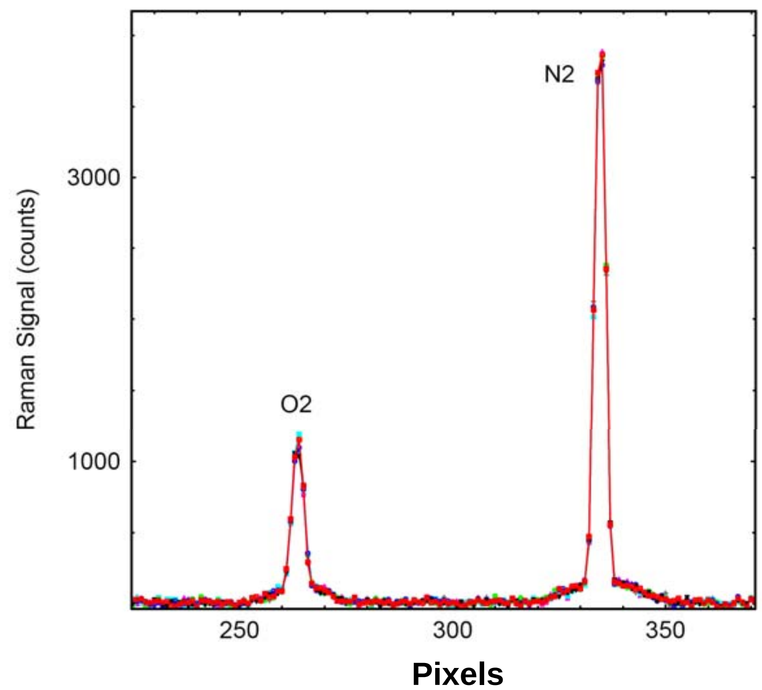


Raman Scattering of Various Gases

20 sec acq. with 30 mW laser

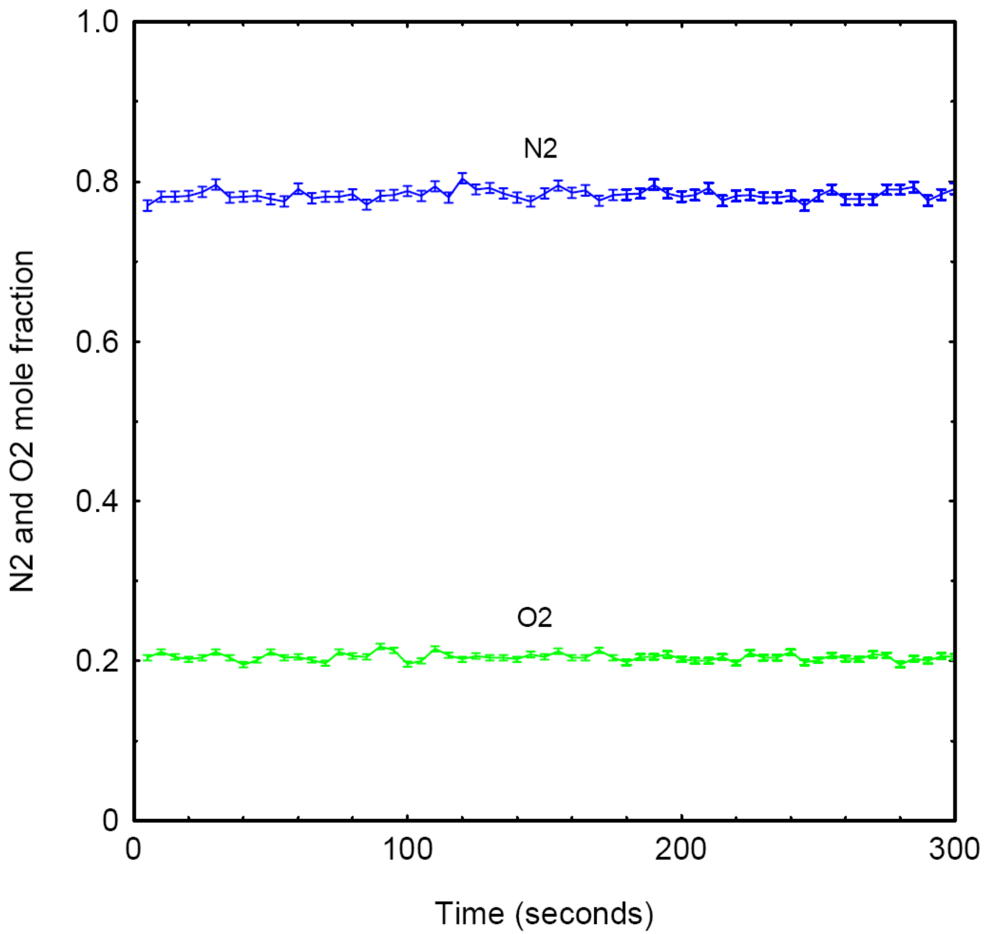


8 different spectra superimposed



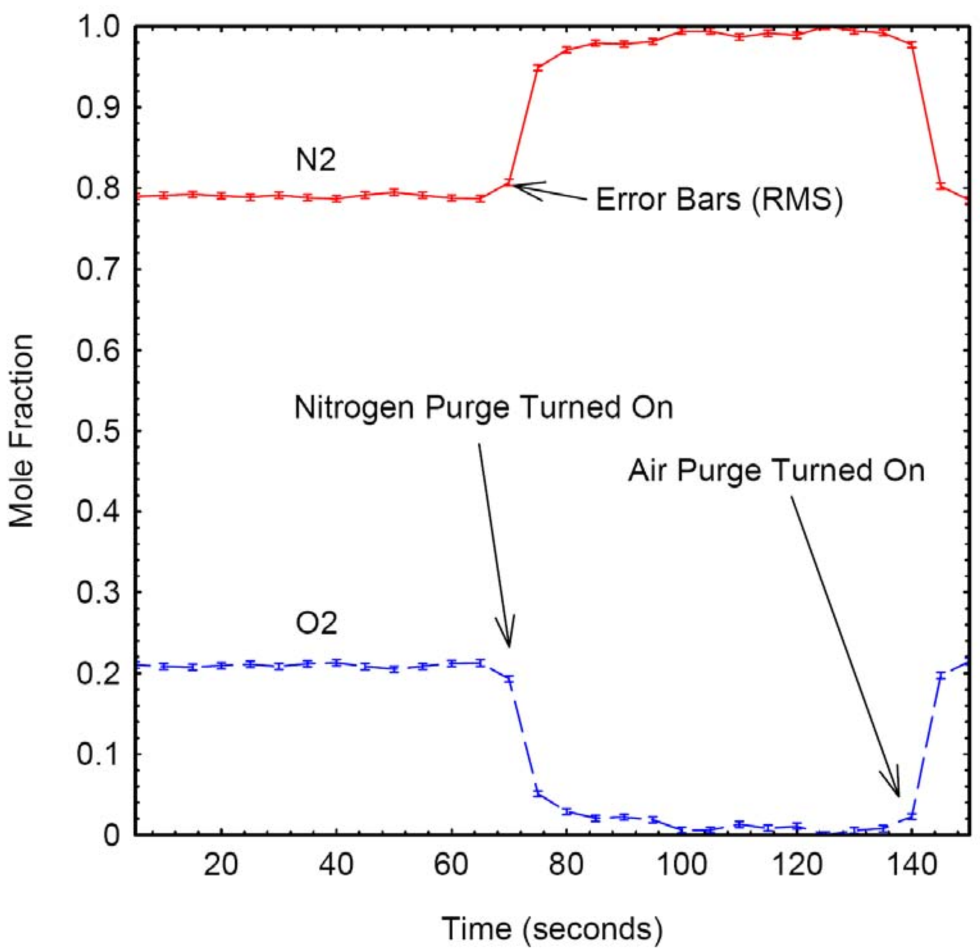
Can also ***differentiate*** the type of HC bonds: saturated vs. un-saturated HC's – volatiles vs. non-volatiles

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



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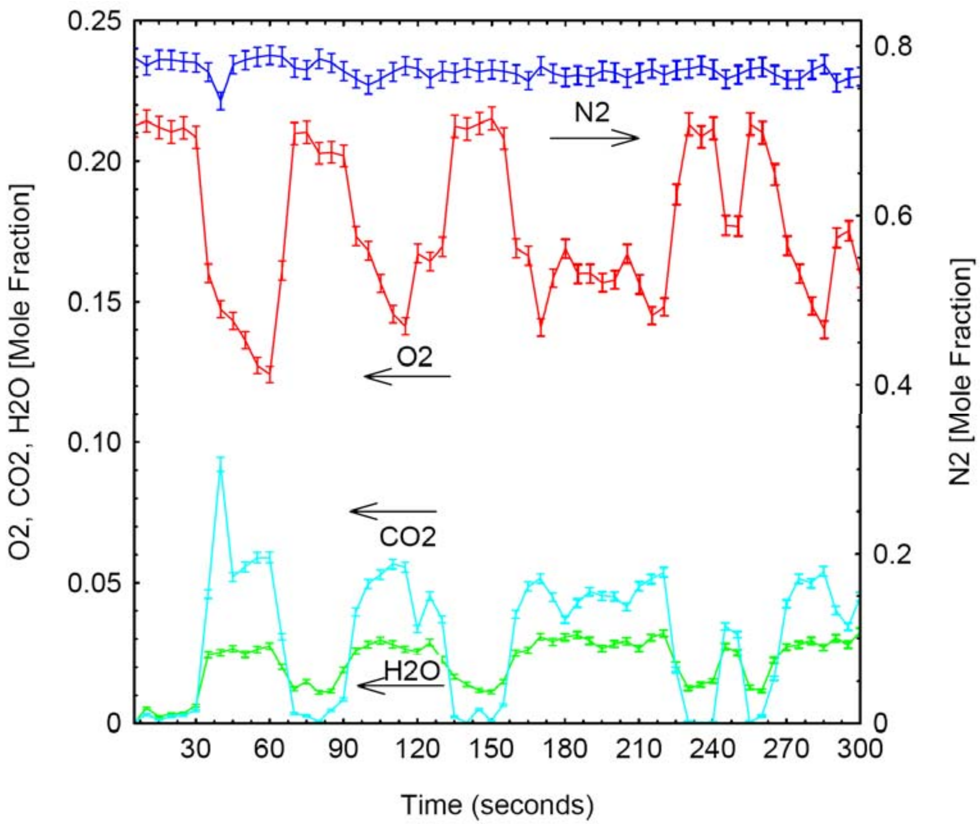
Real-Time Multi-Species Chemical Gas Sensing

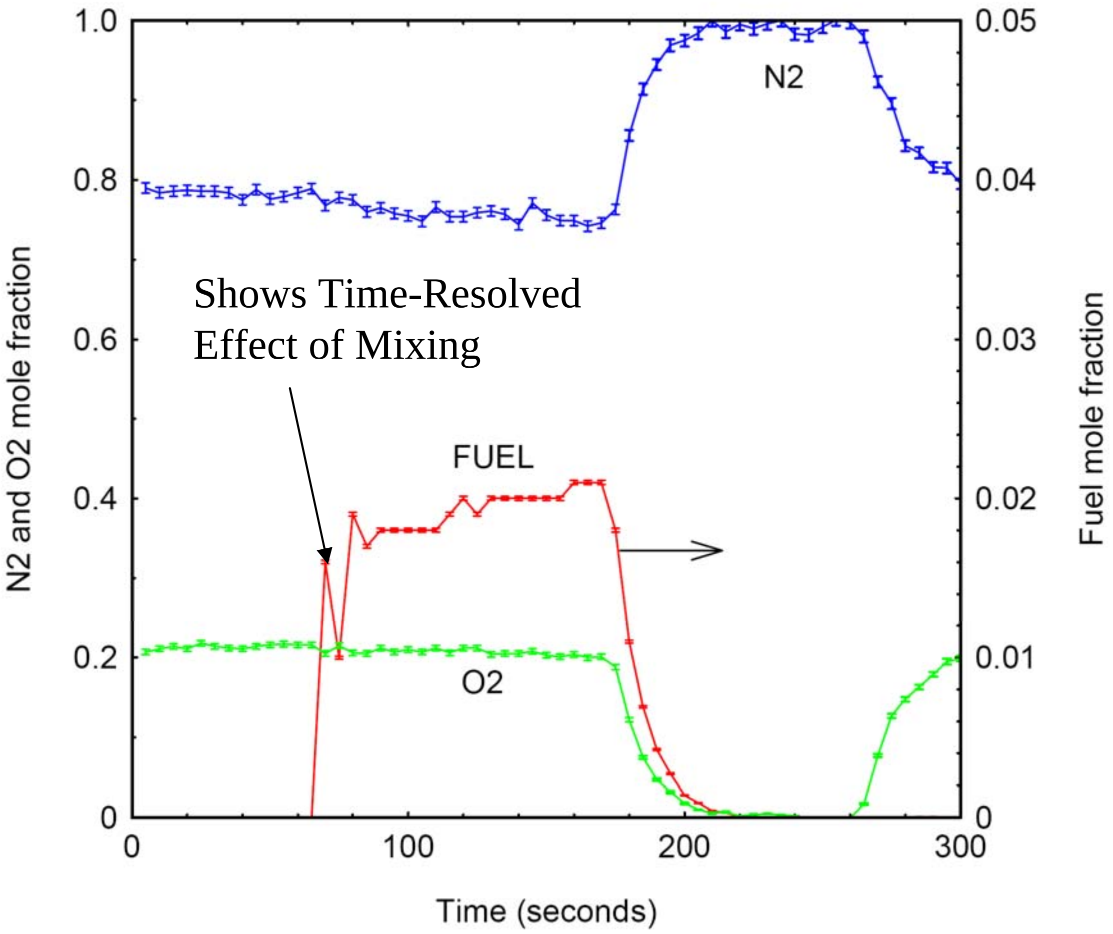
Respiration Gas Monitoring Example



- 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

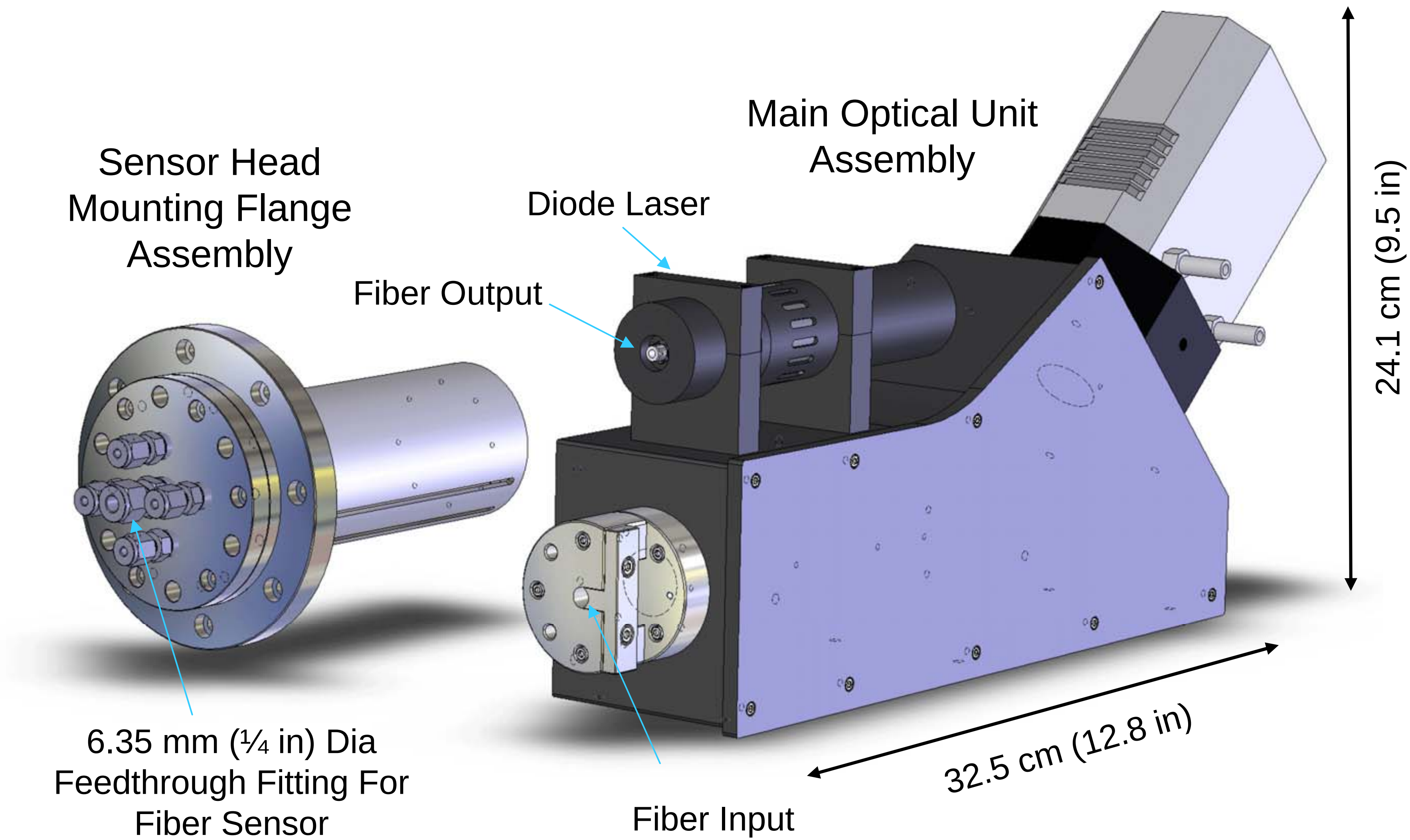
Real-Time Measurement of N_2, O_2, and Fuel

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

CAD Model of Rugged Flight-Capable System



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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.***

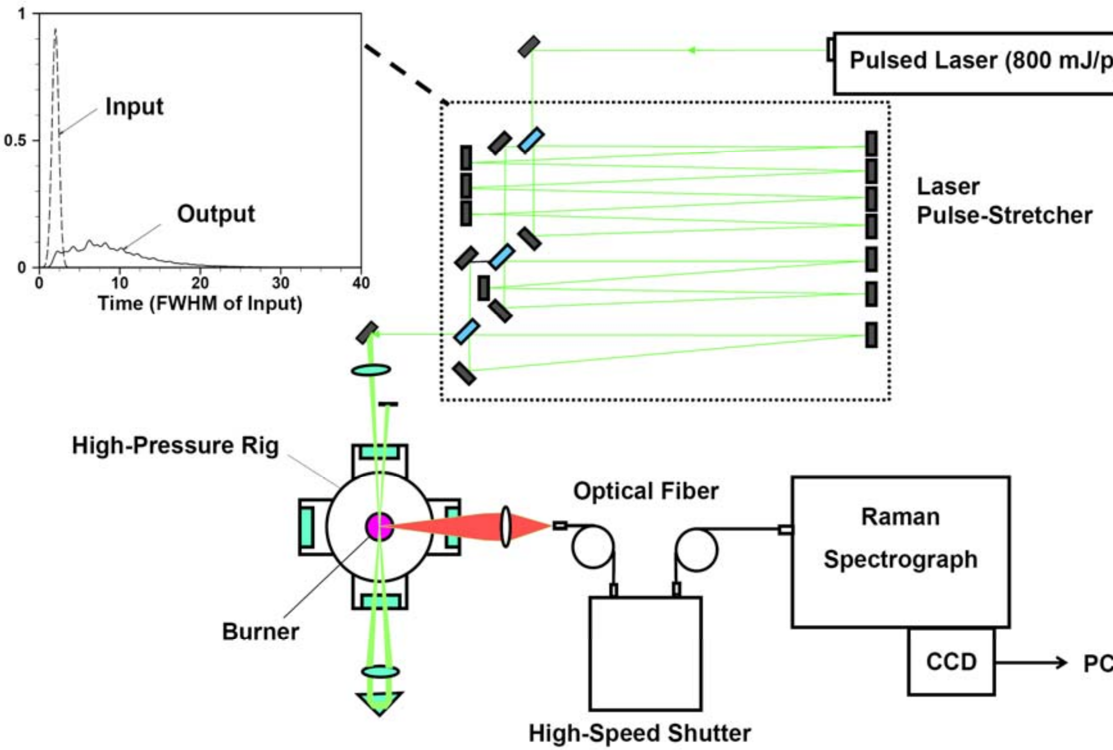
Even if conditions in the fuel tank are susceptible to ignition, the comprehensive nature of the information from the present sensor system ***can potentially predict the risk of damage due to pressure rise.***

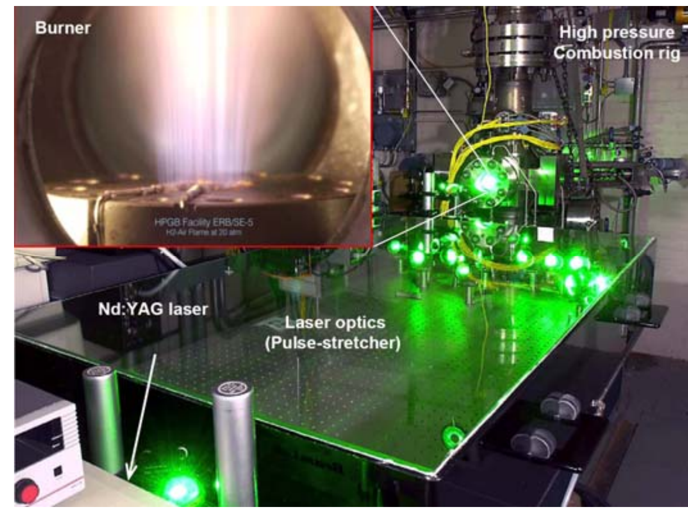
Work Still Needed

- 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…

Supplemental Material

Genesis – Laser Diagnostics in Turbulent Flames





- 60 atm high pressure air-cooled combustion rig with optical access
- Pulsed Raman scattering diagnostics system for multi-scalar measurements
- Facility developed for providing experimental data in high pressure turbulent flames for code validation studies