Aircraft Cabin Environmental Quality Sensors

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NOTICE

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Abstract

Identification of aircraft cabin environmental quality concerns for which sensors may be useful

- The highest priority environmental indicators identified are ozone and cabin air pressure, followed by carbon monoxide and carbon dioxide with moderate priority, and then relative humidity, airborne particles, and organic contaminants, including engine oil byproducts and pesticides. This list is based on the Congressional requirements and recent scientific literature, starting with information from recent studies (NAS/NRC, ASHRAE/Battelle), and continuing by seeking input from a variety of stakeholders.
- The parameters that can be monitored routinely with off-the-shelf sensor technology are ozone, cabin pressure, CO, CO_2 and relative humidity. These formed the prioritized list of environmental parameters for in-flight sensing.

Definition of requirements for sensor and sensor systems

LBNL investigators deduced that sensors intended to provide data for routine use by stakeholders must emphasize simplicity, ruggedness and satisfactory performance with limited attention by the crew and maintenance staff. In order to guide maintenance of environmental control systems and document exposure to contaminants, sensors should be installed at multiple locations in the bleed air and cabin air supply/recirculation system, including the return duct. Packaging requirements for installation and operation on aircraft emphasize simplicity, ruggedness and satisfactory performance with limited attention by the crew and maintenance staff. Within these limits:

- Specific requirements or benchmarks for performance emphasize accuracy (±15%), sensitivity (low ambient levels), and sampling interval (≤60 s).
- Suggested requirements include limitations on the size of sensor elements (≤ 3/8 in diameter), weight of sensor systems (≤1 kg), power (28 V), frequency of maintenance (coincident with service schedules), required operator skill (minimal) and target cost for replaceable sensor elements (≤ $100).

Sensor systems most capable of meeting current requirements.
A survey of sensor systems, parameter by parameter, from highest priority to lowest, is included as Appendix A. Systems chosen for testing were based on principles that are representative of the main approaches that are utilized currently for real-time monitoring of the prioritized parameters. The use of COTS systems simplified the experimental approach because data from their sensors could be acquired without project staff designing and building prototype units. However, no COTS system met all the specifications or benchmarks. To proceed under this limitation, sensors judged to be most capable of meeting requirements were tested in COTS systems based on IR or UV spectroscopy, electrochemical cells, and metal oxide semiconductors. The selected technologies were based on light absorption (UV for ozone and non-dispersive IR for carbon dioxide) and electrochemistry (electrochemical cells and metal oxide semiconductors for ozone and carbon monoxide). Pressure sensors are already standard in aircraft, although the output needs to be logged.

Performance of sensors
Representative sensor technologies were tested in the laboratory under conditions that occur in-flight (cabin air pressure 0.7 to 1 atm; temperature from 65 to 85 °F) and at ground level (relative humidity from 20 to 80%). The results show that neither the EC nor MOS-based sensors responded with at least ±15% accuracy, primarily due to poor reproducibility and hysteresis. The sensors based on light absorption (UV for ozone and IR for CO_2) performed better under the influence of changes in pressure, temperature and humidity than the sensors that depend on electrochemistry (for ozone and CO, analyte-induced redox reactions at sensing and counting electrodes (EC) or at the gas sensing surface of the (HMOS sensor)). The UV-based sensor gave unacceptable performance (> 15% change) only when the relative humidity exceeded 65%, but this condition does not occur in flight because RH rarely exceeds 30%. The optical sensors, both UV and NDIR, need further miniaturization before they can be installed routinely in aircraft.

Recommendations for sensor development
- Circulate the main findings of this study among sensor manufacturers to stimulate development of improved technologies.
- Implement ASHRAE's recommendations for routine monitoring to encourage aircraft-specific sensor designs. When large markets exist for monitoring aircraft cabin environmental quality (ACEQ), developers and manufacturers will have more incentive to miniaturize optical sensors and tailor materials for EC, MOS and other to meet the performance specifications. Costs could approach the benchmark of ≤ $100 per sensor element. (Current EC and MOS sensor elements cost at least twice the target amount.)

Recommendations for future sensor testing
- Broaden the usefulness of the results by evaluating the performance of a larger selection of existing sensors, including GOTS and sensors in the research phase. This would provide stronger guidance for both sensor development and industry-wide monitoring of ACEQ.
- Evaluate the performance of improved sensor materials and assess the performance of systems that become candidates for widespread use in aircraft. A body such as an ASHRAE committee of stakeholders and sensor developers could use LBNL's protocol as a starting point for evaluating improved sensors.
- Use LBNL's protocols to screen sensor systems before more rigorous testing intended to overcome the limitations of this study.
- Test sensor systems for cross-sensitivity to ozone, CO, then add VOC (toluene, terpenes) ethanol and halogen-containing species (pesticides and flame retardants).
- Evaluate using CO/CO_2 ratios to signal incidents caused by pyrolysis products.
- Collaborate with aircraft engineers for in-flight testing of the best available sensor technologies.
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ABBREVIATIONS

As used in this report, the following abbreviations/acronyms have the meanings indicated

ACEQ	Aircraft cabin environmental quality
ACE	Aircraft cabin environment
ACER	Airliner cabin environmental research
ANSI	American National Standards Institute
atm	pressure: 1 atm at sea level
APU	Auxiliary power unit
ASHRAE	American Society of Heating Refrigeration and Air Conditioning Engineers
ºC	Degrees centigrade
CEQ	Cabin environmental quality
CNT	Carbon nanotubes
CO	Carbon monoxide
CO_2	Carbon dioxide
COE	Center of Excellence
Color	Colorimetric
COTS	Commercial off the shelf
ΔP	Change in pressure
ΔRH	Change in relative humidity
ΔT	Change in temperature
EC	Electrochemical cell
ECS	Environmental control system
ºF	Degrees Fahrenheit
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
GAO	General Accounting Office
GOTS	Government off the shelf
H	High
H_2SO_4	Sulfuric acid
HEPA	High efficiency particulate air
HMOS	Heated metal oxide semiconductor
IAQ	Indoor air quality
IEQ	Indoor environmental quality
L	Lower
LBNL	Lawrence Berkeley National Laboratory
LOD	Limit of detection
M	Medium
MEMS	Microelectromechanical systems
MOS	Metal oxide semiconductor
MWCNT	Multiwalled carbon nanotubes
NAS	National Academy of Sciences
NDIR	Non-dispersive infrared
NOAA	National Oceanic and Atmospheric Administration

NRC	National Research Council
O_2	Oxygen
O_3	Ozone
P	Pressure
PAS	Photoacoustic sensor
PdO_2	Palladium oxide
PM	Particulate matter
PO_2	Partial pressure of oxygen
Poly	Polymer
ppm	Parts per million
PtO_2	Platinum oxide
RH	Relative humidity
RITE	Research in the Intermodal Transport Environment
s	second
S	Satisfactory
SARS	Severe acute respiratory syndrome
SiO_2	Silicon dioxide
SnO_2	Tin oxide
T	Temperature
TCP	Tricresylphosphate
U	Unsatisfactory
UV abs	Ultraviolet absorption
Var	Various
VDC	Volts direct current
VOC	Volatile organic compounds
VUV	Vacuum ultraviolet absorption
YSZ	Yttria-stabilized zirconia
ZnO	Zinc oxide

Introduction

The Indoor Environment Department at Lawrence Berkeley National Laboratory (LBNL) teamed with seven universities to participate in a Federal Aviation Administration (FAA) Center of Excellence (COE) for research on environmental quality in aircraft. This report describes research performed at LBNL on selecting and evaluating sensors for monitoring environmental quality in aircraft cabins, as part of Project 7 of the FAA's COE for Airliner Cabin Environmental Research (ACER)[1] effort.

This part of Project 7 links to the ozone, pesticide, and incident projects for data collection and monitoring and is a component of a broader research effort on sensors by ACER. Results from UCB and LBNL's concurrent research on ozone (ACER Project 1) are found in Weschler et al., 2007; Bhangar et al. 2008; Coleman et al., 2008 and Strøm-Tejsen et al., 2008. LBNL's research on pesticides (ACER Project 2) in airliner cabins is described in Maddalena and McKone (2008).

This report focused on the sensors needed for normal contaminants and conditions in aircraft. The results are intended to complement and coordinate with results from other ACER members who concentrated primarily on a) sensors for chemical and biological pollutants that might be released intentionally in aircraft; b) integration of sensor systems; and c) optimal location of sensors within aircraft. The parameters and sensors were selected primarily to satisfy routine monitoring needs for contaminants and conditions that commonly occur in aircraft. However, such sensor systems can also be incorporated into research programs on environmental quality in aircraft cabins.

Background

Aircraft cabin environmental quality (ACEQ) has received increasing attention as the number of passengers has more than quadrupled since the early 1970's. Concern about health impacts of air travel on both crew and passengers led to two reviews by committees of the National Research Council (NRC, 1986 and 2001). The recommendations of the first report led to the ban on smoking on aircraft and a more stringent standard for CO_2.

The second review by the NRC (2001) recommended that an extensive program be conducted to determine compliance with Federal Aviation Regulations (FARs) for air quality, and the effort should include continuous monitoring and recording of O_3, CO, CO_2, fine PM, and cabin P, T and RH. Such a program would sample a large number of flight segments over a relatively short period (at least 100 segments over 1-2 yrs).

A follow-up report by the General Accounting Office (GAO, 2004) led to establishing FAA's ACER Center of Excellence. The GAO report summarized responses of the FAA to the NRC committee's recommendations, reviewed literature such as the 2003 SARS

[1] Renamed to COE for Research in the Intermodal Transport Environment (RITE)

incident, and added information and perspectives from other sources, including the airline industry, aircraft manufacturers and flight crew. The GAO surveyed large US airlines whose aircraft used recirculated cabin air. The GAO learned that 85% used HEPA filters. A large percentage (69%) of smaller aircraft, operated by regional airlines, recirculated cabin air, but very few had HEPA filtration. The GAO pointed out that, in order to identify problems with ventilation and/or air cleaner systems and correct them, aircraft manufacturers needed at least FAA-funded research that would generate monitoring data on ventilation and ozone.

These initiatives produced two studies (Batelle, Part 1, 2004; Part 2, begun in 2007) on ACEQ intended to relate perceptions of discomfort or health-related symptoms of flight attendants and passengers to possible causal factors, including cabin and bleed air quality and factors such as reduced air pressure, jet lag, inactivity, humidity, duty schedules, fatigue, circadian rhythm, stress and noise, in several types of aircraft. The NRC and GAO initiatives also led major stakeholders (aircraft manufacturers, airlines, representatives of crew and researchers) to work together in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) to produce ANSI/ASHRAE Standard 161-2007, Air Quality within Commercial Aircraft (ASHRAE 2008, a voluntary standard for ACEQ (ASHRAE 2008) and to begin drafting a set of guidelines for its implementation. Standard 161 applies to commercial aircraft carrying 20 or more passengers, and it covers ventilation rates, cabin pressure, temperature, and monitoring air contaminants. It is intended to apply to all phases of flight operations and to ground operations when aircraft are occupied by passengers or crew members. The new standard is especially relevant to this project because it requires sensors for ozone and 'incidents' that involve leaks of engine and/or hydraulic fluids.

Rationale: The need to understand and minimize adverse health effects of air travel

Research has determined that concentrations of some air pollutants are often elevated in aircraft relative to typical ground-level outdoor or indoor air concentrations. Because the ozone concentrations at high altitude often greatly exceed those at ground level, passengers and crew may be exposed to higher concentrations of O_3 than are typical inside buildings. People are the major source of the generally higher CO_2 concentrations in aircraft, which can be higher than in most buildings because of the lower rate of outdoor air supply per occupant in aircraft. Passengers and crew experience lower RH, lower air pressure, and potentially lower blood levels of oxygen than on the ground at typical elevations, in addition to more variable T. Organic pollutants emitted from the materials and cleansers used in aircraft, bioeffluents, personal-care products, alcohol, allergens, infectious or inflammatory agents, pesticides and jet exhaust fumes have also been identified as potential concerns within aircraft. Exposures related to 'incidents' (abnormal operation of aircraft engines or components of the ECS) include CO, smoke (fine particles), fumes, hazardous organic gases (including tricresyl phosphate esters, and aldehydes) from leaks of engine oils, hydraulic fluids (hydrocarbons or phosphate esters), and deicing fluids (propylene and ethylene glycols) and their pyrolysis or combustion products (NRC, 2001; Murawski, 2005).

Since the ban on tobacco smoking on aircraft, passengers have continued to report broad and non-specific health complaints, with multiple possible causes, including low humidity, low pressure (i.e., leading to lower blood levels of oxygen), chemical or biological contaminants, psychological and physiological stressors such as fatigue. These stressors may exacerbate some pre-existing medical conditions or may, hypothetically, reduce resistance to infectious disease. Although in one study passengers showed higher risks of upper respiratory tract infections than the general public within a week after their trips, this was not linked to recirculation of cabin air (Zitter et al, 2002). Transmission of severe acute respiratory syndrome (SARS) aboard three aircraft has been linked to the closeness of other passengers (Olsen et al., 2003) and the stage of infection (Bruegelmans et al., 2004).

Low P and thus low PO_2 may cause discomfort in healthy people and more serious effects related to hypoxia (oxygen deficiency) in infants and passengers with cardiovascular or respiratory disease. The fraction of passengers who are children or elderly has increased dramatically since the 1970's, and these groups are more susceptible to adverse effects of air travel than typical adults. Low RH on aircraft has been a suspected cause of discomfort, but a recent study (Strøm-Tejsen et al., 2007) in a simulated aircraft environment found that decreasing outdoor air supply to increase RH worsened, not improved, health complaints. (Decreasing outdoor air supply led to increased concentrations of contaminants originating in the cabin, in addition to higher RH.) Elevated ozone may be encountered in aircraft that are not equipped with ozone scrubbers or that do not have effectively functioning ozone scrubbers. The health impacts of ozone exposure include airway irritation, reduced lung function, exacerbation of asthma, coughing and wheezing. CO, a product of incomplete combustion, causes headaches and lightheadedness at low concentrations. More severe health effects result from prolonged exposure at higher concentrations. Phosphate esters, formaldehyde and other aldehydes, and CO from pyrolysis of engine oils and hydraulic fluids may cause respiratory and neurological effects at high concentrations. At the time of the more recent NRC report (2001), little evidence of adverse effects from these compounds had been reported, but more data have appeared recently (Murawski, 2005). Although individual exposures in isolation may represent only small health concerns, in combination, their influence on health may be more significant, due to additive and synergistic effects. Pesticides used on aircraft have low human toxicity, but they can cause adverse neurotoxic effects at high concentrations (Maddalena and McKone, 2008).

Significance: Meet the need for sensors for routine monitoring of ACEQ

Sensor systems that routinely monitor environmental conditions in aircraft could provide a) information relevant to maintenance needs, such as ozone converter replacement and adjustment of ventilation systems; b) data on compliance with standards and guidelines; and c) data for evaluating the benefits of new environmental control technology. Sensor data would prove useful in recording the frequency and severity of 'incidents,' implementing strategies to reduce excursions and triggering maintenance to reduce exposures related to health impacts. The research community could also use the sensor data to improve understanding of how aircraft environmental quality influences health.

This project focused primarily on selecting parameters and evaluating sensors needed for normal contaminants and conditions in aircraft, with secondary importance placed on selecting parameters that could detect incidents related to leaking hot engine oil or hydraulic fluids. Although commercial off-the-shelf (COTS) sensors are available for indoor air quality (ozone, CO, CO_2, P, T), and there have been efforts to survey possible sensors for aircraft cabin use (Gale et al., 2007), the primary constraints for routine use in civil aviation - low cost and long-term reliability - have not been the main driving factors in previous studies. Trade-offs may be necessary. For instance, incident reporting requires temporal and spatial resolution, but sensitivity is paramount for routine monitoring.

Specific Aims

The specific aims of this project are listed below.

1) Define the highest priority on-board sensing technology needs for aircraft cabin environmental quality,
2) Identify appropriate commercial off the shelf (COTS), government off the shelf (GOTS) and near market sensor technologies,
3) Assess how well these sensor technologies are likely to perform in the cabin, and
4) Identify any necessary modifications.

The results of this project are intended to complement and coordinate with results from other ACER members who concentrated primarily on sensors for chemical and biological pollutants that might be released intentionally in aircraft, integration of sensor systems and optimal location of sensors within aircraft.

Approach

To address the specific aims, the project team performed two scoping tasks and two laboratory tasks, Parts I and II, respectively. Part I identified the main concerns of stakeholders about cabin environmental quality, and then specified sensor requirements (Tasks 1 and 2). Part II selected and evaluated the performance of sensors in the laboratory (Tasks 3 and 4). Part III developed suggestions for future research and development needs for sensors for ACEQ (Task 5).

Part I. Selection of Sensors for Cabin Environmental Quality

Methods

Task 1. Identify environmental quality concerns for which sensors can be useful
Investigators reviewed information from recent reviews, reports and scientific literature, and consulted with stakeholders who will be the primary users of sensor data, including the representatives of the FAA, the aircraft manufacturing and air travel industries. This effort included discussions with COE partners and researchers.

Task 2. Determine sensor and system requirements
Investigators constructed a prioritized list of environmental parameters for in-flight sensing. This list addresses the key environmental quality concerns identified in Task 1. Emphasis was placed on sensors that provide data for routine use by stakeholders (e.g., guiding maintenance of environmental control systems) that could also generate markers for 'incidents' and data for use by the research community.

Investigators then defined specific technical requirements for each of the environmental parameters, including sensitivity, specificity, and sampling interval. More general considerations were also defined, such as limitations on size, weight, power, maintenance cycles, calibration, required operator skill and acceptable cost**.** Consideration was given to where and how sensors systems would be installed in aircraft, in coordination with the work of other ACER COE participants. LBNL assembled information on the sensor 'packaging' requirements for installation and operation on aircraft, including interfacing with other current or future sensors (for example, inter-operability and upward compatibility).

Results

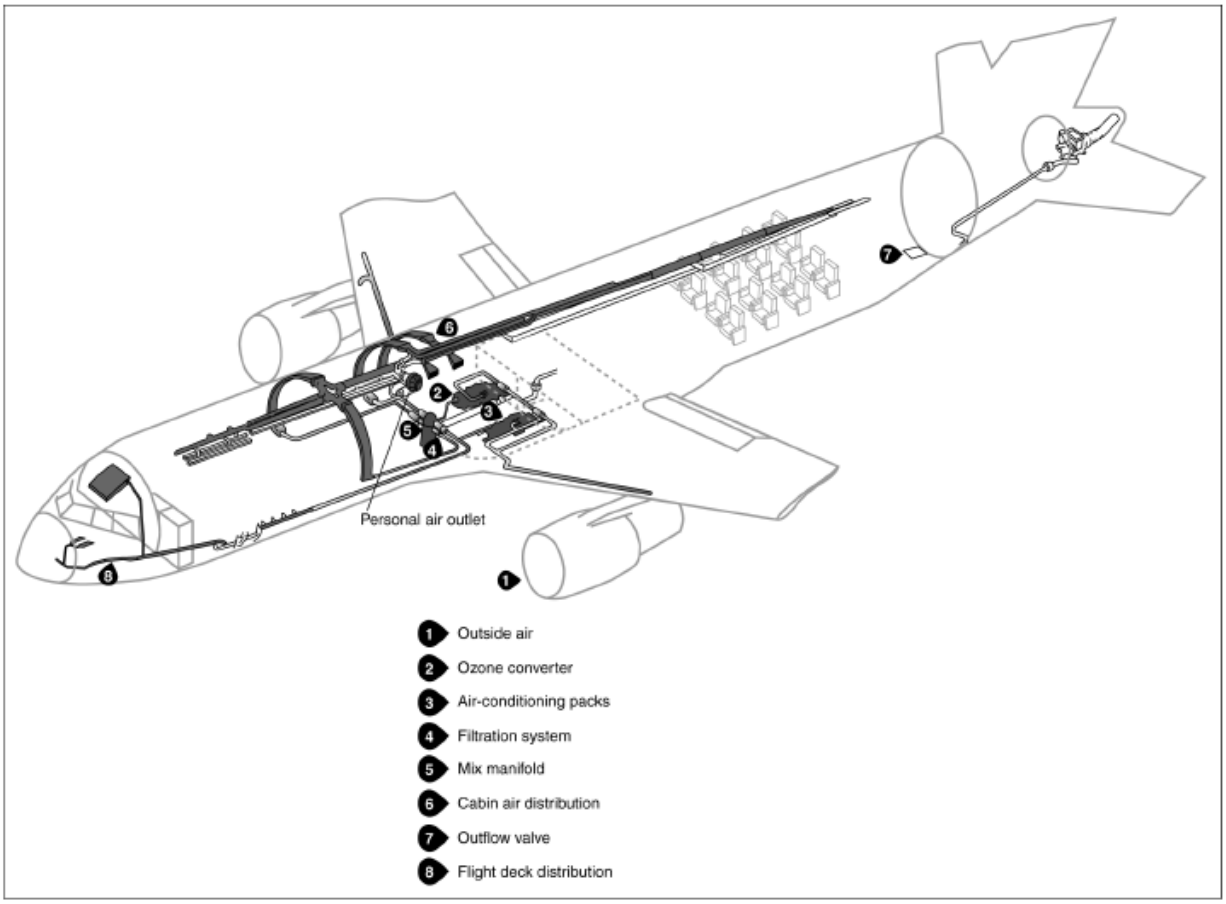
Task 1. Identify the priority environmental quality concerns for which sensors can be useful

The section below summarizes existing information that is relevant to identifying the priority environmental quality concerns for which sensors can be useful. An overview of environmental control systems in aircraft is followed by a brief summary of current FAA

standards and ASHRAE's new voluntary standard (ASHRAE 2008). The section concludes with a list of priority environmental quality concerns that is based on evaluation of available literature, standards and discussions with stakeholders.

Current knowledge

The environmental control system (ECS) in commercial aircraft. The main purpose of the ECS is to allow humans to survive while traveling at altitudes and (outside) pressures that are hostile to life. The ECS is designed to meet FAA standards and provide a safe and healthful environment in the passenger cabin. Its main components are shown in Figure 1, a schematic diagram adapted from the GAO report (2004) and discussed in detail by Hunt et al. (1995). Long-range passenger jets actually have two sets of most of the components shown in Fig. 1, with one originating on each side of the aircraft. Cabin air is typically half outside air, referred to as bleed air, that is taken from the compressor stages of the main engines (1), upstream of the combustion zone, scrubbed (2) of ozone while still hot (if the plane is equipped with an ozone converter), then conditioned (3) and mixed with filtered cabin air (4) in the mix manifold (5). The air is distributed to the cabin (6) along the main axis of the aircraft, as well as to individual air outlets. The circulation pattern is designed to limit axial mixing. Air that will not be re-circulated passes overboard through an outflow valve (7) at the rear of the plane. The flight deck (8) receives 100% conditioned outside air (for heat dissipation). Some aircraft use 100% outside air, but this is not typical because it increases fuel consumption.



Source: Reproduced with permission from the Boeing Company.

(1) Outside air continuously enters the engine, where it is compressed.

(2) It then passes through a catalytic ozone converter (in some aircraft) to air-conditioning packs.

Figure 1. Supply system for cabin air for Boeing 767 aircraft (the GAO report (2004).

The ECS controls cabin P, T and ventilation rate, and most systems currently minimize the introduction of harmful particulate contaminants (e.g., bacteria, secondary aerosols) by passing cabin air through high efficiency particulate air (HEPA) filters before it is re-circulated. Except for ozone, current designs do not remove other pollutants from the outside air or contaminants that leak from components of the engine or the ECS itself.

Federal Aviation Regulations for ACEQ. The ECS must meet the FAA's design and operational specifications, known as Federal Aviation Regulations, for O_3 (0.1 ppm above altitudes of 27,000 ft and peak concentrations of 0.25 ppm above 32,000 ft), CO_2, ventilation, and cabin P. The FAA also requires that aircraft maintain air pressures equivalent to pressures at altitudes below 8000 feet, where the partial pressure of oxygen is about 75% of the value at sea level. The NRC report (2001) noted that the current design standard for ventilation rate per person is less than two thirds of the ventilation rate recommended by ASHRAE for commercial buildings.

Contaminants, potentially uncomfortable and/or hazardous conditions. Exposure to contaminants and potentially harmful conditions depends on the flight segment. At the airport the cabin air is primarily influenced by outside air whose delivery to the cabin is controlled by the auxiliary power unit. Thus the cabin air often contains outdoor pollutants from nearby sources while the aircraft is on the ground (CO, PM, diesel fumes, de-icing fluids). In the event that engine seals begin to fail in-flight, the lubrication and hydraulic systems in the engines and ECS components can become sources of contamination. Since the compressors and air conditioning packs operate at high temperatures for some portions of the flight, not only engine lubricants and hydraulic fluids can infiltrate cabin air, but also their pyrolysis products and CO. At cruise altitudes ambient O_3 (elevated at high latitudes in spring) will penetrate into the cabin air if scrubbers are not used or if their effectiveness is diminished. On-board operations and occupants can generate alcohol, nuisance odors, bio-aerosols and contaminants associated with pesticides and cleaning products. Pesticide concerns have been raised by passengers and crew because they are sprayed on some international flights, but scant quantitative data exist for exposure to these compounds in aircraft cabins.

The NRC report (2001) classified exposures into two categories: those occurring under routine conditions (e.g., reduced PO_2, bioeffluents from passengers, O_3 in ventilation air at high altitude cruise, organic compounds from cleaning agents, and infectious agents, allergens, and irritants) and those occurring during non-routine events ('incidents,' e.g., intrusion of lubricating, hydraulic fluids, deicing fluids or their degradation products).

ACEQ on commercial flights. The first part of the ASHRAE-sponsored Battelle study collected passenger complaints and monitored ACEQ on four commercial flights using instrument packages that fit under the passenger seats (Battelle, Part I, 2004). Most of the passenger complaints were related to low RH, reduced pressure, and elevated noise. ACEQ-related measurements showed that carbon monoxide levels were well within guidelines. Average ozone concentrations ranged from 30 to 110 ppb, but on one flight cabin and bleed air ozone concentrations were 170 and 190 ppb, respectively. More recent measurements showed generally moderate ozone concentrations in the aircraft cabin that almost always complied with the FAA standard (Bhangar et al., 2008). Measurements of VOCs at cruise altitude in the Battelle study showed that ethanol (from alcoholic drinks) and acetone (a bioeffluent and also a byproduct of ozone-induced oxidation of skin oils) were dominant VOCs. No VOC sampling was conducted before take-off, thus no information was gained about infiltration of VOCs from ground level sources such as idling engines. Naphthalene was the most abundant semivolatile organic compound. Air exchange rates were estimated from carbon dioxide data, and they were within guidelines.

The second part of the ASHRAE-sponsored study by Battelle got underway in 2007, and it is addressing these objectives:

1. Characterize and quantify contaminants in cabin air that are introduced via ECS.
2. Measure ventilation rates and characterize contaminants in cabin air that are not introduced via ECS.

3. Quantify the effect of aircraft type, maintenance, APU, engine age and operations-related parameters on cabin and bleed air quality.
4. Investigate the relationship of the measured cabin air contaminants, ventilation rates and other factors with reported symptoms of passengers and crew.

ASHRAE Standard 161-2007. In mid-2008 the voluntary ANSI/ASHRAE Standard 161-2007 *Air Quality within Commercial Aircraft* appeared, after 14 years of effort by stakeholder-experts from the aircraft and airline industries, as well as crew and passenger representatives. The standard requires a temperature range of 65-75 °F, for both crew and passenger areas, and it sets upper limits to acceptable ozone concentrations (≤ 250 ppb at any time; ≤ 100 ppb for any consecutive 3-hr period), lower limits to ventilation rates for outside (7.5 ft^3 min^{-1} or 3.5 L s^{-1} per person) and total air flow (15 ft^3 min^{-1} or 7.1 L s^{-1}) per person, as well as maximum rates of ascent and descent. (Assuming occupant density of 0.5 person m^{-2}, ASHRAE 62.1-2007 would require from 3.1 L s^{-1} $person^{-1}$ to 10.6 L s^{-1} $person^{-1}$ in buildings.) Of specific relevance to this project, the standard recommends that sensors be installed in the air supply system to monitor sources of bleed air contamination from engine oil or hydraulic fluid during 'incidents.' The standard recommends separate sensors for each engine and the auxiliary power unit (APU). The standard also specifies procedures to document complaints and to log data when sensors indicate release of contaminants. The sensor data are to be displayed in the flight deck and recorded whenever a trigger point is exceeded. Procedures are described for preventing and remedying exposures to ozone, hydraulic fluid, exhaust, fuel, ozone, pesticides, among others. These actions, if widely adopted, would improve cabin environmental quality and generate better records of the frequency and severity of 'incidents.'

Prioritizing environmental quality concerns

NRC's monitoring priorities. The NRC report (2001) identified critical outstanding questions that sensors could help address. The first asked if aircraft comply with FAA regulatory limits for ventilation rate, ozone (3 h averages of 0.1 and 0.25 ppm at altitudes below 27,000 and 32,000 ft, respectively), carbon dioxide (5000 ppm) and carbon monoxide (50 ppm). The NRC report also raised questions about the FAA design standard for ventilation (4.7 L s^{-1} $person^{-1}$).

In addition to a routine monitoring (surveillance) program, the NRC report recommended that the FAA demonstrate that the existing FARs for air quality (CO, O_3, ventilation and pressure) are adequate to protect health and are met by commercial aircraft. Data generated could also be used to record the frequency and severity of incidents when contaminants bleed into the cabin, as well as the association between cabin air contaminants and health effects. This recommendation influenced ASHRAE to sponsor the Battelle studies (Part I, 2004; Part II, 2007). The GAO report (2004) also pointed out that aircraft manufacturers need FAA-funded research that generates monitoring data on ventilation and ozone in order to identify problems with ventilation and/or air cleaner systems and correct them.

Table 1 summarizes the parameters that the NRC (2001) recommended for routine monitoring of cabin environmental quality. The committee assigned high priority for further investigation of reduced PO_2 and elevated O_3, noting that health-compromised and infant passengers could experience a variety of respiratory symptoms related to these environmental quality parameters.

Table 1. The NRC's priorities for routine monitoring of environmental characteristics and contaminants, based on potential health effects and frequency of exposure (NRC 2001).

Priority		
High	***Moderate***	***Low***
Cabin pressure	Airborne allergens	CO_2
	CO	De-icing fluids
Ozone	Hydraulic fluids/engine oils (& degradation products)	Nuisance odors
	Infectious agents	RH, T
	Pesticides	

Exposure to biological agents, particularly airborne infectious agents, had not been documented in aircraft, but the high occupancy density and close proximity of passengers appeared to be important to infectious disease transmission, whereas aircraft ventilation systems did not appear to affect transmission. These concerns were borne out in 2003, when severe acute respiratory distress (SARS) was transmitted in-flight (Olsen et al., 2003; Breugelmans et al., 2004). Other aircraft characteristics or air contaminants were not expected to affect health during routine operations, with the possible exception of low RH that can cause temporary discomfort to eyes and mucous membranes.

Stakeholders' perspectives on priority environmental quality issues and potential uses for sensor data. At the start of the project in 2006, investigators sought informal input from major stakeholders in the airline industry. Representatives of the flight attendants' union, aircraft manufacturers, passengers (LBNL travelers) and researchers were contacted by phone and email. Prior to LBNL's final selection of parameters for testing sensors, stakeholders were asked to identify and prioritize the cabin environmental quality issues and sensing parameters of importance to their communities. Table 2 summarizes the issues raised in these discussions. The most frequently mentioned purpose for the sensor data given by each stakeholder group is listed in the top row next to the stakeholder's name. The LBNL researchers were unsuccessful in reaching airline representatives with whom to discuss ACEQ. Therefore, Tables 2 and 3 include the investigators' impressions of the airlines' perspectives.

Table 2 shows that the FAA and organizations such as ASHRAE support improved ACEQ industry-wide. Data from sensors can monitor compliance with existing and voluntary standards for ACEQ. Aircraft manufacturers and airlines typically accept the likelihood of requirements for sensors and urge simplicity and low cost. Industry-wide

requirements would share the burden of implementation. Crew members want healthful and safe working conditions, and data from sensors could provide ongoing documentation of both routine ACEQ and incidents. Passengers want safe, low-cost travel that does not make them sick, and some travelers have expressed interest in being able to access monitoring data after incidents. The research community needs sensor data on ACEQ and concurrent documentation of health impacts to investigate the links between environmental quality and health, as well as implement the NRC's recommendations.

Table 2. Cabin environmental quality issues relevant to stakeholders.

Stakeholder	Sensor-Related Issues
Regulatory agencies	Compliance with FARS and ASHRAE Standard
Aircraft manufacturers	Safety, low cost, simplicity, maintenance alerts, aircraft ECS design improvements. 'level playing field'
Airlines[a]	Revenue, passenger comfort, minimal complaints, 'level playing field'
Crew	Documenting exposures to contaminants (hydraulic fluids, pyrolysis products, pesticides); health risks; chemical sensitivity; compliance with standards; discomfort; access to data
Passengers	Health risks, comfort, access to data
Researchers	Exposure data related to health research and aircraft design improvements; access to data

[a] The issues noted are those anticipated by the research team whose members were unable to obtain input directly from the airlines.

Table 3 shows how stakeholders' concerns about ACEQ (Table 2) translate into priorities for sensors. From the regulators' perspective, the priorities for sensing must support monitoring compliance with standards. This criterion implicitly mandates sensors for ozone, CO, CO_2, pressure and temperature. Aircraft manufacturers in general place higher priority on sensors that could warn of unsafe conditions and thus may be more interested in monitoring VOC concentrations than temperature in the cabin. (Pressure and temperature are monitored in real time on board, but data are not logged for the duration of the flight.)

Table 3. Stakeholders' priorities for sensors for ACEQ, as understood by LBNL staff. The top five are indicated as high (H), followed by medium (*M*) and low (L) priorities.

Parameter	FAA and ASHRAE: FARs, aircraft performance	Aircraft manufacturers: cost, design	Airlines: revenue, passenger comfort[1]	Crew: exposure assessment	Passengers: comfort and protection	Researchers: data on health & aircraft performance
O_3	**H**	**H**	L	**H**	*M*	**H**
P	**H**	**H**	L	*M*	**H**	**H**
CO	**H**	**H**	L	**H**[2]	**H**	**H**
CO_2	**H**	**H**	L	***M***[2]	*M*	**H**
RH	*M*	*M*	L	*M*	**H**	*M*
T	**H**	*M*	L	**H**	**H**	**H**
VOC[3]	*M*	**H**	L	*M*	*M*	*M*
TCP[4]	*M*	*M*	L	**H**	L	*M*
PM[5]	L	*M*	L	*M*	L	*M*
Biological effluents	L	L	L	*M*	**H**	*M*
Pesticides	*M*	L	L	**H**	L	*M*

[1] These priorities have been assigned based on the authors' understanding of the airline industry, and they have not been reviewed or endorsed by anyone associated with the airline industry.

[2] As indicators of incidents related to presence of engine oil, hydraulic fluid and/or their pyrolysis products in the cabin air.

[3] Volatile organic compounds.

[4] Tricresylphosphate, an additive to hydraulic fluid and lubricating oils.

[5] Particulate matter.

Crew members' targets for sensing are based on the importance of ongoing assessment of exposure to species that are known or suspected to be harmful to human health in the workplace. Thus, their highest priorities are ozone and indicators of the intrusion of additives from engine oil, hydraulic fluid, and their pyrolysis products (e.g., tricresylphosphate or CO and CO_2 as tracers for TCP), in addition to pesticides. Crew members also value temperature logging in their work and rest areas. When queried about sensors for ACEQ, passengers prioritize parameters that relate directly to safety (CO and infectious agents) or comfort (pressure, temperature and relative humidity). As a whole, researchers have the same priorities as the FAA and ASHRAE, but value acquiring as much data as possible to relate ACEQ to health and aircraft performance. Generally, crew members and researchers showed reluctance to assign low priority to any parameter.

Prioritized recommendations for indicators of environmental quality on commercial aircraft: O_3, P, CO, CO_2

The literature review and input from stakeholders led to selection of the cabin-environmental quality indicators that are shown in Table 4 and discussed below. Prioritization is based on the potential health implications of the parameters, the expected usefulness of the data and the current availability of appropriate sensors.

The availability of sensors was assessed through a preliminary survey of current approaches to monitoring candidate indicators of cabin environmental quality. Parameters for which no routine monitoring technology is currently (2009) available were assigned lower priority, with recognition that monitoring priorities may change if suitable sensor systems were to become available.

Table 4. LBNL's selection of priority environmental quality indicators for routine monitoring of environmental characteristics and contaminants, based on literature review and discussions with stakeholders.

Priority		
High	***Moderate***	***Lower***
Ozone	CO	RH, PM[2], VOC[3]
Cabin pressure[1]	CO_2	ozone reaction by-products,[3] engine and hydraulic oil/by-products,[3] pesticides[3]

[1] Currently measured but not recorded; temperature is also not recorded.
[2] Lower priority because of the current unavailability of reliable, low-cost sensors to identify sources of particles; routine sensing of PM need not be a high priority in aircraft that have HEPA filters.
[3] Lower priority because of the current unavailability of reliable, low-cost sensors to identify contaminants or their sources

First Priority: Sensors for Ozone and Pressure

LBNL investigators recommend that elevated ozone and reduced oxygen partial pressure be considered as the two air quality characteristics that should be given the highest priority for further investigation, based on their potential health impacts and likelihood of occurrence. Aircraft often encounter high ozone concentrations and not all aircraft are equipped with ozone destroying converters. Commercial aircraft always experience low atmospheric pressure. Ozone sensors were judged to be the highest priority. Pressure sensors are already present in aircraft; thus, the only additional requirement would be to log the pressure data.

Second Priority: Sensors for Carbon Monoxide and Carbon Dioxide

Although CO_2 is generally not considered an air contaminant, and evidence suggests that concentrations in aircraft are generally below the FAA limit, monitoring CO_2 can provide an indicator of the adequacy of ventilation. Ventilation, or the replacement of cabin air with outside air, is the primary method of reducing exposure to many contaminants. LBNL recommends sensing both carbon monoxide and carbon dioxide because monitoring both CO and CO_2 (with current COTS) could be a low-cost strategy to track incidents in which the decomposition of engine fluids would elevate the ratio of CO to CO_2. At present, reliable low-cost sensors are not available for near real-time monitoring of individual constituents of engine fluids or their decomposition products, and most stakeholders recognize the merits of recording the frequency and severity of incidents.

Third Priority: Sensors for Other Cabin Characteristics of Concern

The list of contaminants or environmental characteristics of concern includes allergens, hydraulic fluid and engine oils and their partial decomposition products (in addition to carbon monoxide), ozone reaction byproducts (e.g., aldehydes), infectious agents, pesticides, relative humidity, and noise. LBNL recommends assigning lower priority to sensing components of this group at present because, except for RH and noise, practical near-real time sensors are not yet available or expected for at least five years. For example, the issue of pesticides is not really amenable to sensor technology at this point so the low priority given to this contaminant does not diminish its potential importance. There are almost no relevant measurements on aircraft and until observations are made, via monitoring on treated aircraft, it is impossible to say that pesticide exposure concentrations do or do not need to be monitored. Noise-related health concerns were not uncovered in the literature. Low relative humidity, while common in aircraft, is generally considered to be of low concern because it has not been shown to cause adverse health affects beyond temporary drying of skin, eyes and mucous membranes. At present there is no evidence of increased transmission of colds in airplanes, but low RH has a greater effect on passengers with respiratory infections or asthma (Rayman, 1997), probably due to reduced clearance of mucus (Berglund, 1998).

Many of the lower priority contaminants circulate as airborne particles (allergens, infectious agents, and some of the decomposition products of engine and hydraulic fluids). The risk of exposure to infectious agents cannot be completely eliminated due to passenger proximity, and the recirculation of air on the aircraft does not exacerbate exposure to particles if the air passes through a HEPA filter. On most large aircraft, recirculation reduces exposure to particulate air contaminants because the cabin air is filtered prior to recycling. Current sensor technology for particle mass, particle number and size distribution can not discriminate adequately among the possible sources of particulate matter in the cabin air.

In addition to particulate matter exposure, incidents involving engine oils and hydraulic fluids may result in exposure to various volatile and semi-volatile organic compounds,

but current instrumentation for real-time monitoring of individual constituents does not meet the requirements for use in routine monitoring of ACEQ. Exposure to pesticides (disinsection agents) concerns some stakeholder groups because disinsection is done during some international flights. Real-time off-the-shelf sensors for airborne pesticides are not yet available.

Task 2: Determine sensor and system requirements for monitoring ACEQ routinely

The objective of this task was to identify critical specifications for sensors that can routinely monitor the indicators of ACEQ that were identified in Task 1 (Table 4). Many of the requirements are similar to those described in the ACER survey of sensor technology for chemical and biological threats (Gale et al., 2006). However, besides selectivity, accuracy and sensitivity, requirements for routine monitoring must place higher priority on simplicity, affordability, unattended operation, integration with existing electronics and ease of data retrieval. Tables 5 and 6 summarize, respectively, the packaging/operational and technical requirements that apply to all the environmental parameters and contaminants that are to be monitored routinely aboard aircraft.

The discussions with representatives of the aircraft manufacturers and crew members indicated that the more seamlessly sensors and their electronics integrate into existing aircraft systems and operations, the less resistance their adoption will face from stakeholders, and the more likely the sensor systems will generate data that meet the needs of the stakeholders. For successful implementation of routine monitoring programs, the requirements must be met with systems that require minimal modification of existing aircraft and do not burden ground or flight crews. Table 5 incorporates the perspectives and recommendations of aircraft manufacturers and crews for evaluating the suitability of existing COTS and GOTS for retrofitting existing commercial aircraft, and incorporating future sensor systems into designs for new aircraft.

Table 5. Packaging and operational requirements for sensors that monitor ACEQ.

Characteristic	Target	More detail
Operation	As simple as possible	Automatic, non-distracting operation; real-time display for crew; data retrievable at end of flight; no post-flight processing by crew
Display	Flight deck (all parameters)	Crew work areas (selected parameters)
Calibration	Infrequent or factory set	
Maintenance	Simple and infrequent	
Warm-up-time	Ready when crew members board	
Durability	Very low maintenance	One flight-year without maintenance, if possible; linked to service intervals
Consumables	None	
Location	Bleed air and return ducts; multiple locations within the passenger cabin (both sides)	Transducer elements inserted into ducts and cabin via existing ports; signals processed in central instrumentation/data collection area (avionics rack)
Cost	As low as possible, < $100 per sensor	Reliability paramount

The general technical specifications (Table 6) are best met by sensors whose transducers are small enough to be inserted into the type of ports that are already used in the mixing manifolds that supply air to the cabin. These ports are incorporated during the manufacture of the fiberglass ducts that will later be installed in the cargo hold. Sensors that meet this requirement can also be used to monitor the air that exits the cabin before part of it is filtered and mixed with clean air for recirculation into the cabin.

Table 6. Technical requirements (benchmarks) for sensors that monitor ACEQ.

Characteristic	Target	More detail
Selectivity	Minimal false positives and negatives (<1 in 10^6); minimal cross-sensitivity	Somewhat less critical for ACEQ sensors than for chem-bio sensors[1]
Accuracy	Acceptable performance compared to standard methods (± 15%)	Under ground and flight conditions (0.7 to 1 atm; 10-65% RH; 65-85 °F)
Sensitivity	Low ambient concentrations to twice expected maxima	Under flight conditions; unaffected by other species or characteristics or cycling of T, RH, P
Sampling frequency	Time resolution at least 1 min	Selectable frequency and data averaging
Power	28 VDC	Attach to power bus[2], low power (a few watts maximum)
Interference	Minimal noise, vibration, electromagnetic fields	Operation and signals unaffected by other onboard instruments
Interfacing and communication	Integrate with existing data collection systems (wired, avoid wireless at present)	Plug-and-play capability with systems developed by ACER partners; data retrievable from flight deck
Upgradability	Seamless: plug-and-play[3]	During periodic maintenance
Calibration	Pre-set, automatic or simple to perform	Accurate for both ground and flight conditions[4]
Location and number	Bleed air and return ducts; multiple locations within the passenger cabin; both sides of the air handling system	Transducer elements inserted into ducts and cabin via existing ports; signals processed in central instrumentation/data collection area (avionics rack)
Size	Sensing element (≤ 3/8 in diameter, button type) fits into existing ports in the air supply manifold (½ inch diameter); insertion directly into plenum is possible.	Including signal monitoring and data processing, smaller than a breadbox or toaster oven, including multiple sensors
Weight	As light as possible	Less than 1 kg for each parameter, including multiple sensor locations

[1] In contrast to chem-bio sensors, false positives (or negatives) of more than 1 in 10^6 in sensors for ACEQ are likely to be acceptable to airline industry.
[2] Usually accessible on aircraft (power bus, cargo compartment)
[3] Avoid 'turnbacks'
[4] Referenced to published standard methods

Table 6 is based on the researchers' synthesis of information from stakeholders and literature, and it is not intended to be exhaustive. The specification for accuracy (± 15%, under flight conditions, compared to standards) allows for some expected drift, hysteresis and pressure-dependent response under flight conditions. The specification for sampling frequency (1 min or less) is intended to allow for pinpointing the time of incidents that could be traced by the monitors for ACEQ.

Part II. Performance of Sensors under Simulated Flight Conditions

Methods

Task 3. Identify GOTS/COTS systems most capable of meeting current requirements
Based on the sensor priorities and requirements developed in Tasks 1 and 2, LBNL reviewed the sensor technologies currently available, considering near- and long-term needs. The review of GOTS/COTS and near-market technologies included input from COE staff and industrial partners. Sensors and sensor packages were then selected for testing. When possible, at least two sensor systems with different detection principles were chosen for each pollutant.

Task 4. Assess performance of sensors
LBNL developed protocols for testing the performance of sensors for ozone, CO and CO_2 using typical in-flight pressure profiles, over realistic ranges of temperature and RH. This was done in collaboration with COE and industrial partners, with input from the FAA. A set of criteria was established against which sensor performance was assessed.

LBNL encouraged sensor manufacturers to modify existing sensors to meet requirements and provide prototypes for performance testing. However, the sensors that were supplied in COTS units were not modified before evaluation. Laboratory testing was performed with only those sensors whose advertised specifications were judged to have the best chance of meeting the requirements for ACEQ.

Task 3: Identify GOTS/COTS systems that meet current requirements

In 2006 LBNL investigators began a survey of sensors with the primary purpose of identifying commercial off the shelf instruments that could meet the requirements for monitoring ACEQ. The secondary purpose was to show what directions the developers of sensors are taking. Appendices A1 through A5 contain the survey of sensor systems that are already commercialized, emerging into the marketplace and currently in the research and development phase, for each priority parameter (Part I). This effort benefited from two related projects: the survey of sensor technology for chemical and biological agents prepared by Gale et al. (2006) and evaluation of sensor performance by Battelle (2004) in preparation for their program to monitor ACEQ (2007).

Overview of sensor technology for routine real-time monitoring of ACEQ

Introduction: At the heart of all sensor systems lie the sensing elements that respond to nearby changes in physical or chemical characteristics and the transducers that convert the responses to electrical signals. Other core components are controllers, data loggers and communication ports. COTS sensor systems can be self-contained devices such as clip-on CO monitors for personal exposure, or several sensor / transducer components may be remotely connected to electronics that handle signals for multiple sensors simultaneously. Sensor systems are typically packaged as COTS devices to meet specific needs, for example, monitoring CO_2 in HVAC systems or CO in homes.

Detection principles: Candidate sensors for routine monitoring of ACEQ use three main principles. Chemical sensors depend on chemical reactions between the target gases and the sensing material. Many COTS devices use chemical sensing (electrochemical cells or conductivity of metal oxide semiconductors) for O_3 and CO, and a few are marketed for CO_2 and VOC. Stetter's review (2003) gives a good introduction to chemical sensors. Optical sensors measure absorption of light by the species of interest, and infrared absorption is widely used in COTS devices for CO_2. Reference methods for CO/CO_2 and O_3 use IR and UV absorption, respectively. The most widely used COTS sensors for atmospheric pressure and relative humidity are physical sensors that respond non-destructively to their surroundings by changing their capacitance or piezoresistance (pressure-dependent resistance). Since sensing technology for pressure and humidity is mature and already widely used in aircraft, the survey includes only a few examples of sensor systems for these parameters. The survey does not cover sensors for VOC, pesticides, ozone by-products, hydraulic fluid or engine-oil by-products, because no suitable sensor systems are currently available for routine monitoring.

Chemical sensors (O_3, CO, CO_2, VOC)

Electrochemical cells. Electrochemical sensors have two electrodes that are embedded in or in contact with an electrolyte that can be liquid, solid or gel. In the amperometric sensor illustrated on the left side of Figure 2, CO diffuses through a porous membrane to the working electrode where it is oxidized to CO_2. Ambient O_2 is reduced to water at the counter electrode. The reaction generates a current that is proportional to the concentration of CO. Ideally the current follows Faraday's law, and the sensor is sensitive only to CO. In the sensor shown on the right side of Figure 2, the two electrodes are separated by a solid electrolyte (in this case, yttria-stablized zirconia, for monitoring O_2). For this potentiometric sensor the concentration of O_2 is related to voltage necessary to keep the current zero (through the Nernst equation). Many gas sensors are based on monitoring the interfacial potential at the surface of a solid electrolyte that has been coated with a material that undergoes a reversible redox reaction with the target gas.

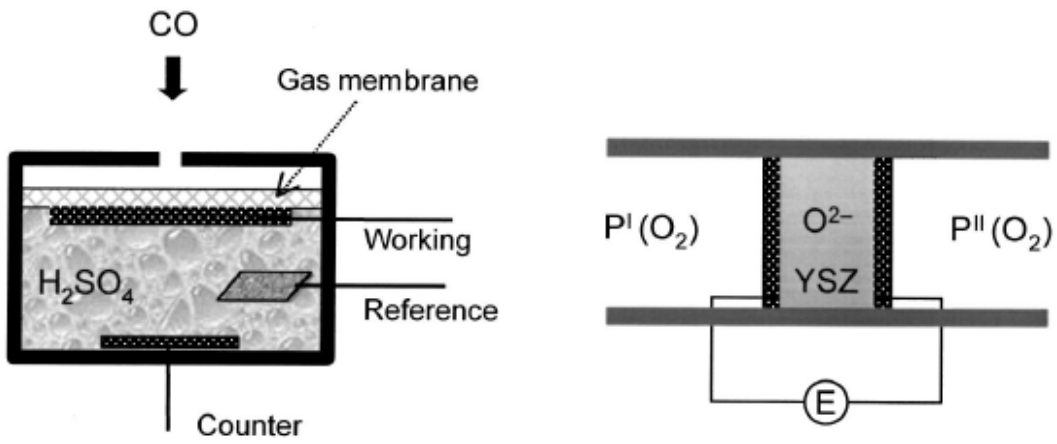


Figure 2. Electrochemical sensors: (left) amperometric (current generating) with liquid electrolyte, for CO; (right) potentiometric (voltage generating) with solid electrolyte, for O_2, from Stetter et al., 2003.

Conductivity sensors. Figure 3, adapted from a review by Arshak et al. (2004), shows three views of a planar conductivity sensor. When the sensing material (top view) is a thin film of an n-type semiconductor such as ZnO, SnO_2 or TiO_2, ambient O_2 pulls electrons from its surface, increasing the electrical resistance of the MOS film. The conductivity of the MOS layer increases in the presence of reducing gases such as carbon monoxide. This is due to the electron-releasing reaction of the analyte with negatively charged surface oxygen species (O_2^- or O^-). Selectivity of MOS films is dependent on the temperature to which they are heated as well as the composition of the sensing material. MOS films composed of p-type semiconductors have increased conductivity in the presence of oxidizing gases like O_3. The heater is shown from the bottom in the lowest section of Figure 3. The middle view shows how the electrodes contact the MOS film.

Most commercially available conductivity-based sensors use metal oxide semiconductors as the sensing material, but gas sensors based on conducting polymers and/or carbon nanotubes are emerging into the marketplace to act as 'electronic noses' for volatile organic gases (Arshak et al. 2004).

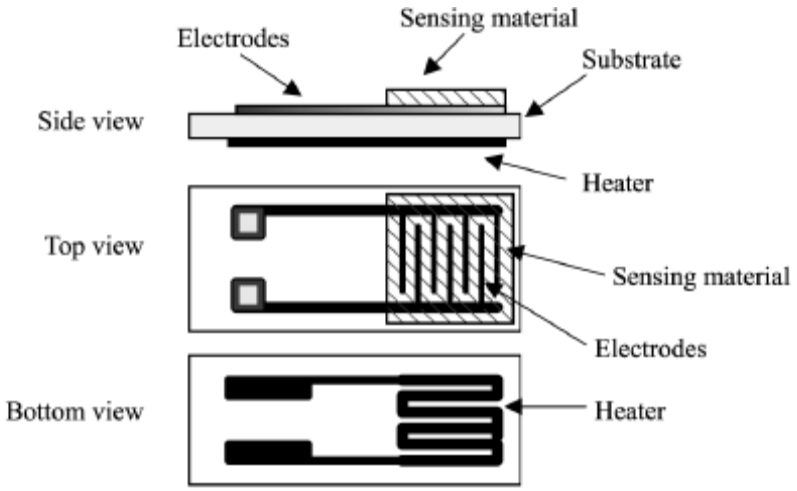


Figure 3. Diagram of a conductivity sensor for gas sensing. From top to bottom: the thin film of sensing material, typically a metal oxide semiconductor, has been deposited onto electrodes (middle) that sit on a non-conducting substrate. The heater has been deposited onto the base of the substrate, as shown in the lowest section of the diagram. Adapted from Arshak et al., 2004.

Optical sensors (O_3, CO, CO_2)

UV absorption. Because ozone has been designated as a hazardous air pollutant for which EPA mandates measurements, this project has taken advantage of EPA-approved instrumentation as the standard for evaluation of the performance of ozone sensor systems. The reference method is based on monitoring UV absorbance by ozone at 254 nm. Figure 4 shows the configuration of a COTS instrument that applies this sensing strategy in a simple optical train (Bognar and Birks, 1996). While the airstream passes through the absorption cell, the transmission of light from a low pressure mercury lamp is monitored by a photodiode. Ozone concentration is derived by applying the Beer-Lambert law.

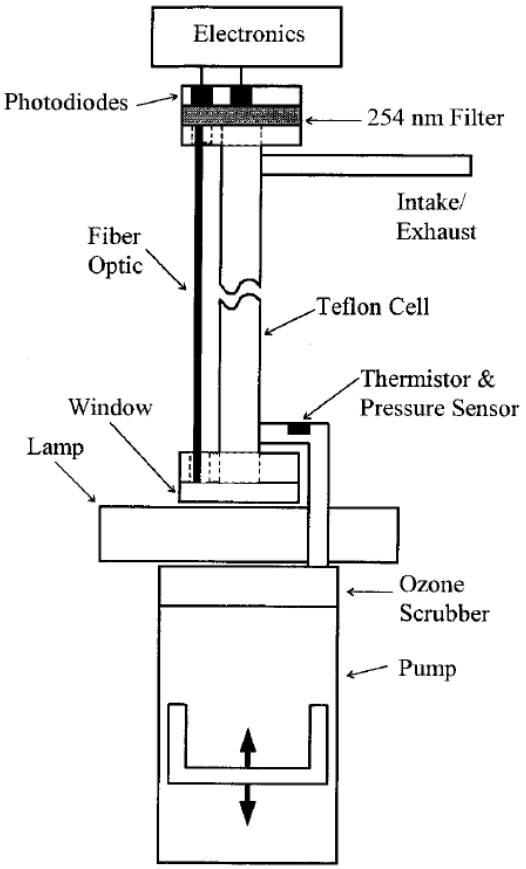


Figure 4. Diagram of ozone monitor based on ultraviolet absorption. Adapted from Bognar and Birks (1996).

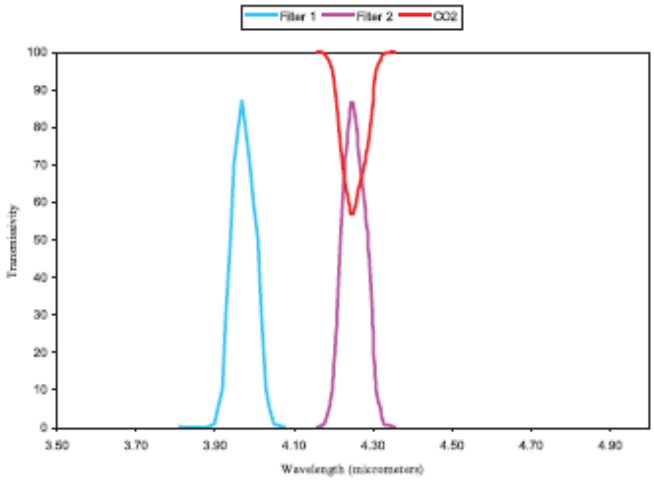


Figure 5. Non-dispersive infrared spectroscopy for monitoring CO_2. (From *S. Shrestha and G. Maxwell, Wall Mounted Carbon Dioxide (CO_2) transmitters, National Building Controls Information Center Product Testing Report, June 2009).*

IR absorption. The red (dark shaded) line in Fig. 5 shows that CO_2 absorbs IR at 4.26 μm. (CO absorbs IR at 4.6 μm.) The purple (medium dark) line illustrates the light transmission of a filter used to measure CO_2 concentration from the Beer-Lambert law. The blue (lightly shaded) line shows transmission through a filter that passes only light in a wavelength range were neither CO_2 nor water absorb. Most COTS devices for CO_2 use one of the four configurations shown in Fig. 6. All but the one shown in Fig. 6 (a) use one filter at the CO_2 absorption peak for transmitted light intensity I and another that is blind to CO_2 and water to derive a drift corrected value for I_0 (for intensity at 4.2 μm with no CO_2).

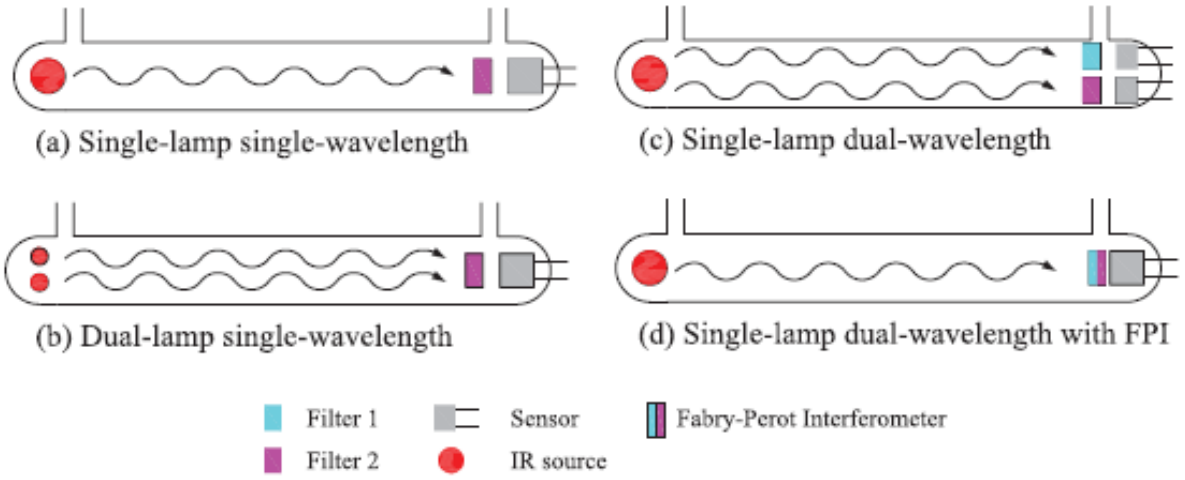


Figure 6. Typical configurations of optics in sensing systems for CO_2. (From S. Shrestha and G. Maxwell, 2009).

Transmitted light intensity is monitored at the wavelength of peak absorption by CO_2. The simplest configuration is shown in Fig. 6 (a) in which the response is calibrated periodically by assuming the ambient concentration is 400 ppm in ambient air at sea level. Identical lamps are used in (b). The flash rate differs for the two lamps, so that signals from the lamp that operates less often can be used to correct for drift in signals from the lamp that operates more of the time. (c) Light from a single lamp is monitored at two wavelengths, one of which is 4.2 μm. The signal from the other wavelength provides the drift correction as the lamp ages. In (d) the drift correction for the single lamp is based on light transmitted through a Fabry-Perot interferometer whose transmission band is controlled electronically. Single lamp configurations are more widely used in COTS systems than dual lamp systems, and among these, dual beam configurations account for less than half of those available.

Suitability of the sensor technologies for monitoring ACEQ: Table 7 summarizes the strengths and weaknesses of the sensing approaches that were outlined above, based on reading the literature and considering the technical requirements for routine monitoring of ACEQ (Table 6). Electrochemical and HMOS sensors are small enough to fit into ports in the air supply manifold, and the cost of sensor elements may not be prohibitive for placement at multiple locations in the air supply system. Neither of the optical

methods described above has been miniaturized so that the sensor element could fit into a small port on the manifold. That may not be necessary for CO_2 because it is not likely to react with materials used in sampling lines. Because of its reactivity, ozone must be quantitated at the sampling port. However, the available literature indicates that the responses of EC and HMOS sensors are susceptible to changes in pressure, relative humidity and temperature, and they may have cross-sensitivities to other gases besides the intended analytes. Sensor systems using these principles are unlikely to meet many of the technical specifications of Table 6.

Table 7. Strengths and weaknesses of sensor technologies for CO, CO_2 and O_3

Principle and species	Strengths	Concern 1	Concern 2	Concern 3
Electrochemical cell				
CO, O_3	Low cost, low power, small, real-time; more sensitive than MOS	Interferences: CO, VOC	Sensitive to ΔP, ΔRH, ΔT	Drift, frequent recalibration needed, 1 yr lifetime
Non-dispersive infrared absorption (4.26 µm)				
CO_2	Compact, stable to ΔRH , ΔT	Sensitivity depends on path length	Calibration may be misinterpreted or inaccurate	Some single beam devices auto-calibrate as if background CO_2 is 400 ppb
Ultraviolet absorption (254 nm)				
O_3	Accuracy, stable to ΔP	Size (not yet miniaturized)	Sensitive to ΔRH	Cost
Heated metal oxide semiconductor				
CO, O_3	Small size; stability, long lifetime, inexpensive	Sensitive to ΔP, ΔRH, ΔT; cross-sensitivity	Power consumption; fragile materials	Typically less sensitive than EC

Survey of sensor systems for ACEQ

Although many kinds of sensors are used throughout aircraft, at present no COTS devices are marketed for the specific purpose of monitoring O_3, CO or CO_2 at multiple locations during commercial flights. Therefore, the survey of available sensors focuses on COTS devices that use sensing principles and architecture that could be integrated into current

avionics. The survey includes only systems whose published specifications indicate that they could meet at least half of the packaging, operational and technical requirements described in Tables 5 and 6. Excluded are COTS devices that require frequent replenishment of reagents or more technical skill than using a cellular telephone. However, the survey, though exhaustive, could not realistically uncover all the manufacturers and supplies of sensor systems for common pollutants. Exclusion is not intended to imply inappropriateness, nor is inclusion an endorsement.

The stages of sensor development are indicated as *COTS, emerging* and *research.* The types of sensors that are currently being commercialized or have recently appeared in the marketplace fall into the 'emerging' stage, and those that are described only in the technical literature are considered to be in the 'research' stage.

Table 8 summarizes the distribution of sensing principles that the research team found for each parameter at each stage of development. The survey tables are included as Tables A1 through A5 in Appendix A. Each parameter has a separate table, and the tables appear in order of priority for monitoring ACEQ. Although representative sensors for pressure and humidity are included in the survey (Tables A2 and A5, respectively) the search for them was not extensive because the technologies are mature.

Ozone: Appendix A1 has detailed information and references for ozone sensor systems. COTS devices typically use sensors with electrochemical cells or heated metal oxide semiconductors. They usually have sensing elements and transducers that are small enough to fit into the ports of the air manifolds on aircraft. At present the instruments that use ultraviolet absorption have optical paths that are much too long for use in multiple locations in aircraft, and they are expensive. Colorimetric sensors were included because they could be worn by crew members or mounted unobtrusively as indicating badges. If properly calibrated they could yield integrated exposure data. The only emerging sensor that the survey found has an electrochemical cell. Most devices in the research stage use sensors with metal oxide semiconductors of various types.

Pressure: Because pressure sensing is a mature field, Appendix A2 has only a few illustrative references to COTS instruments, including a review.

Carbon monoxide: Appendix A3 and Table 8 show that more COTS systems are available with electrochemical cells (9) than with MOS (3) or other technologies. The survey uncovered four research studies whose objectives involved developing CO sensors based on the conductivity of single or multiwalled carbon nanotubes.

Carbon dioxide: The survey results in Appendix A4 and Table 8 show that NDIR is a mature sensing technology for CO_2. Selection of NDIR-based sensor systems for CO_2 on aircraft should carefully consider the design of the optical system and the method of calibration. Carbon nanotubes have promise for conductivity-based sensing of CO_2 in small devices in the future.

Table 8. Summary of sensor survey: distribution of detection principles and stages of development for sensors with potential for routine monitoring of ACEQ in aircraft.

		Number of Sensor Systems		
Parameter	**Detection Principle**	**COTS**	**Emerging**	**Research**
Ozone	Colorimetric	2	-	1
	Diffusion (passive sampling)	1	-	-
	Electrochemical cell	5	1	-
	Luminescence	2	-	1
	Metal oxide semiconductor	3	-	10
	Polymer resistance	-	-	1
	Ultraviolet absorption[1]	2	-	-
Pressure	Piezoresistive	many	-	-
Carbon monoxide	Carbon nanotube resistance	-	-	4
	Conductivity of coated porous Si	-	-	1
	Electrochemical cell	9	1	-
	Infrared absorption[1]	2	-	1
	Metal oxide semiconductor	4	1	1
	Photoacoustic spectroscopy	1	-	-
	Vacuum ultraviolet absorption	-	-	1
			-	
Carbon dioxide	Carbon nanotube resistance	-	-	3
	Conductivity of coated porous Si	-	-	1
	Electrochemical cell	1	-	1
	Infrared absorption[1]	10	1	-
	Photoacoustic spectroscopy	1	-	-
Relative humidity	Capacitive	4	-	-
	Carbon nanotube resistance	-	-	1
	Infrared absorption[1]	1	-	-
	Metal oxide semiconductor	-	-	1

[1]Reference instrument

Selection of sensor systems for laboratory testing

The selection of sensor technologies for evaluation was intended to be representative of the distribution of sensor principles used in currently available COTS instrumentation for relatively inexpensive real-time monitoring of ozone, CO and CO_2. Three types of sensors were chosen for monitoring ozone: UV absorption, electrochemical cells and conductivity-based metal oxide semiconductors. The reference instrument for ozone

used UV absorption. For carbon monoxide, electrochemical and MOS sensors were selected, and, for carbon dioxide, nondispersive infrared absorption was the logical choice for both the reference and test sensors. The reference method for CO also used NDIR.

For convenience and simplicity LBNL used COTS devices with minimal modification because the sensors were already packaged with transducers and associated electronics. However, the selection was made to evaluate the performance of the sensors technologies, not the COTS sensor systems as instruments or analyzers. Outfitting commercial aircraft with multiple sensors at multiple locations in the aircraft will require customizing the configuration of the components for data logging, processing and communication.

Task 4. Assess performance of representative sensors

Ozone, carbon monoxide, and carbon dioxide instruments with different sensing technologies – spectrophotometry, heated metal-oxide semiconductors (HMOS), and electrochemical cells – were evaluated to assess in relative and absolute terms how they could be expected to perform on aircraft. The experimental program subjected the analyzers to changes in air pressure, temperature, and humidity. No GOTS systems were used in the chamber experiments because any requirements for routine use in the near future limit the selection to COTS systems.

Table 9 lists the sensing technology and specifications of the COTS devices acquired or borrowed for this study. Two categories of analyzers are given for each pollutant: reference and test. Reference analyzers used research-grade spectroscopic sensing technologies – infrared absorption for carbon monoxide and carbon dioxide and ultraviolet absorption for ozone – and their data provided the basis for evaluating the performance of test analyzers. The reference carbon monoxide analyzer (TECO 48C) is a U.S. EPA Designated Method (RFCA-0981-054), and the reference ozone analyzer (API 400) has been designated by the U.S. Environmental Protection Agency as an equivalent method (57 FR 44565). Test analyzers, even those employing spectroscopic sensing technology, were considerably smaller and less expensive than the reference analyzers.

Methods

Experimental chamber. Experiments were performed in the 208 L stainless steel chamber shown in Figure 7. The chamber lid was removable and equipped with ports for power, gas injection, sampling, and sensing P, T and RH. A mixing fan was located under the lid. Calibration and experimental design are discussed below.

Calibration. Test and reference carbon monoxide and carbon dioxide analyzers were calibrated daily prior to each chamber experiment. The response of each analyzer was

recorded when subjected to zero and span gases. Span gases were prepared using a gas divider (STEC/Scott) that blended carbon dioxide or carbon monoxide (certified concentrations in N_2) with zero air. The span gases filled aluminum sampling bags and were used to produce multipoint calibration curves from 0 to 2400 ppm of carbon dioxide and 0 to 40 ppm of carbon monoxide in dry air.

In this study the reference ozone analyzer was calibrated as a transfer standard by the California Air Resources Board and periodically compared with a second identical instrument. The zero and span of test ozone analyzers were periodically determined by comparison with the reference ozone analyzer using step-wise increasing ozone concentrations. During these comparisons, test ozone analyzers were placed inside the experimental chamber, and the reference ozone analyzer sampled through a Teflon tube connected to a port through the chamber lid. Closed loop recirculation of air from the chamber through columns of activated carbon and desiccant supplied initially ozone-free, dry air to the chamber. Ozone produced by a corona discharge ozone generator in the hood was tapped at a t-fitting by a syringe (5-10 cm^3) as the ozone was directed outdoors through the hood vent. Ozone was injected into the chamber from the syringe while the concentration was monitored by the reference instrument. Ozone concentration was increased incrementally by approximately 30 ppb every 20 minutes by injecting more O_3 or by varying the power supplied to an ultraviolet lamp that extended though a port in the chamber lid. This procedure was used to produce multipoint calibration curves over the range from 0 to 150 ppb of ozone (in dry air).

Rather than adjusting the internal calibration settings of the analyzers, any calibration adjustments were applied to the raw signals generated by each analyzer during the chamber experiments. There were two notable exceptions. 1) The internal calibration of the OMC-1108 electrochemical ozone analyzer was altered because its response was far below that specified by the manufacturer's calibration record. 2) Calibration adjustments were not applied to the Aeroqual S500 carbon monoxide analyzer, which was slow in responding to changes in calibration gas concentrations and largely unresponsive to low concentrations of carbon monoxide. These exceptions are discussed in more detail below.

Experimental Design. Test analyzers were placed inside the stainless steel chamber and subjected to conditions of changing pressure, humidity, and temperature. Pollutant concentrations measured by the test analyzers were compared to those of the reference analyzers that were located outside of the chamber and generally isolated from the changing environmental conditions of the chamber. A typical experimental setup is shown in Figure 7. The temperature, pressure, and humidity inside the chamber were measured using sensors inserted through ports in the chamber lid. Test instruments recorded data with on-board data storage or data were recorded with externally connected loggers (inside the chamber). Data from the reference analyzers and sensors for T, P and RH were recorded with an external logger.

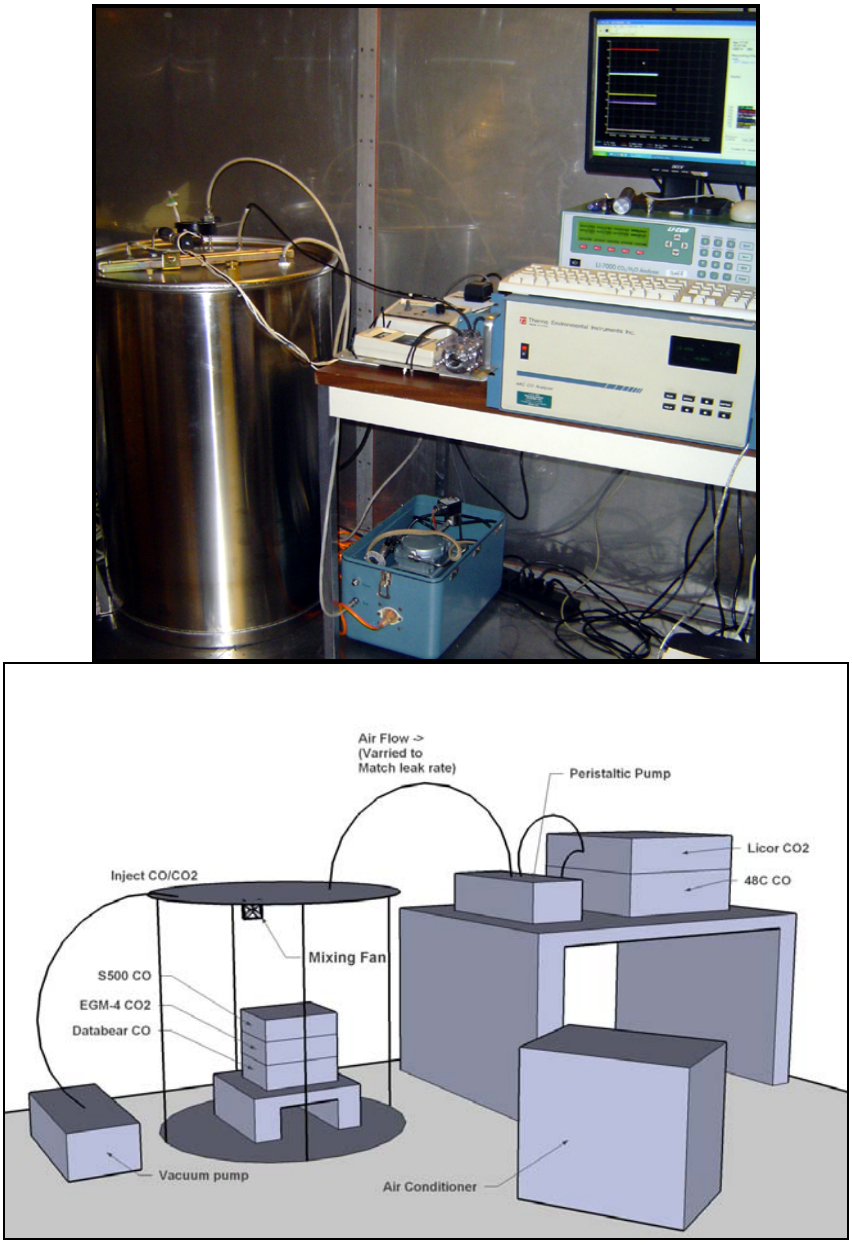


Figure 7. The experimental setup for evaluating the performance of carbon monoxide and carbon dioxide sensors under varying pressure: Test analyzers were inside the stainless steel chamber and reference analyzers (at ambient pressure) were on the table next to the chamber.

Table 9. Reference and test analyzers in this study, with the manufacturers' specifications.

					Manufacturers' Ratings			
Analyzer	**Reference or Test**	**Sensor Technology**	**Range**	**Accuracy**	**Precision**	**Environmental Limits**	**Response Time**	**Price $ 2009**
CO Analyzers								
TECO Model 48C	Reference	IR absorption	0-100 ppm[1]	±1 %	0.1 ppm	41 to 113 °F	60 s	11,000
Langan DataBear, Model T15d	Test	Electrochemical Cell	0 – 127.5 ppm		0.5 ppm	23 to 104 °F	≥ 1 s	1,375
TSI Q-Trak Plus, 8554	Test	Electrochemical Cell	0-500 ppm	greater of ±3% of reading or 3 ppm	0.1 ppm	41 to 113 °F	< 60 s	2,935
Aeroqual Series 500[4]	Test	Heated Metal Oxide Sensor	0-1000 ppm	< ±10%	1 ppm	32 to 158 °F 5 to 95% RH	< 150 s	1,395+445
CO_2 Analyzers								
LI-COR, Model 7000	Reference	Differential, Non-dispersive IR absorption	0-3000 ppm	1%	0.01 ppm	41 to 113 °F	Fast – 0.02 s Slow – 1 s	17,500
TSI Q-Trak Plus, 8554	Test	Non-dispersive IR absorption	0-5000 ppm	±(3% of reading + 50 ppm)	1 ppm	41 to 113 °F	20 s	2,935
PP Systems EGM-4	Test	Non-dispersive IR absorption	0-5000 ppm[2]	better than 1%	10 ppm	32 to 158 °F	1.6 s	4,500
O_3 Analyzers								
API, Model 400	Reference	UV absorption	0 to 200 ppb[3]	better than 1%	1 ppb	10-90% RH 41-104 °F	> 20 s	7,650 basic 12,000 all
2B Technologies, Model 202	Test	UV absorption	0 to 100 ppm	1.5 ppb or 2%	0.1 ppb		10 s	4,500
Aeroqual Series 500[4]	Test	Heated Metal Oxide Sensor	0 to 1 ppm	< ±8 ppb (O_3 < 100 ppb)	1 ppb	23 to 122 °F 5 to 95% RH	< 60 s	1,395 + 395
OMC-1108	Test	Electrochemical Cell	0 to 9.99 ppm	±10%	10 ppb	32 to 104 °F 0 to 80% RH	> 70 s	1,095

[1] User selectable up to 10,000 ppm, a 100 ppm range was selected in this study.
[2] User selectable from 1000 to 20,000 ppm; a 5000 ppm range used in this study.
[3] User selectable from 100 ppb to 10 ppm; 200 ppb range used in this study.
[4] The Aeroqual S500 has swappable heads for different gases.

Table 10. Details of the chamber experiments.

Date	Expt.	Analyzers Evaluated	Details (see text)	Primary Variable(s)[x]	Appendix Figures
5/18/2007	1	*O_3:* 2BTech, S500	Step changes in pressure between 1.0 and 0.7 atm; low (20-30%) relative humidity	P	B1, C1, D1-D4
5/21/2007	2				
5/24/2007	3				
5/25/2007	4	*O_3:* 2BTech, S500, OMC			
5/29/2007	5				
6/13/2007	6	*CO:* 48C, S500, Databear	Step changes in pressure between 1.0 and 0.7 atm; low (15-25%) relative humidity	P	B2, C2, D5-D9
6/14/2007	7				
6/15/2007	8	*CO_2:* EGM-4, CO: 48C, S500, Databear			
6/18/2007	9				
3/22/2007	10	*CO_2:* EGM-4, Q-Trak, *CO:* 48C, Q-Trak	Step changes in pressure between 1.0 and 0.7 atm; higher (20-70%) relative humidity	P	B3, C3, D10-D14
3/23/2007	11				
3/26/2007	12	*CO_2:* EGM-4			
3/27/2007	13	*CO_2:* EGM-4, Q-Trak, *CO:* 48C, Q-Trak			
4/6/2007	14	*CO_2:* Q-Trak, *CO:* 48C, Q-Trak			
6/4/2007	15	*O_3:* 2BTech, S500, OMC	Start at < 20% RH, increase to 80% RH, then let RH decrease	H	B4, C4, D15-D25
6/5/2007	16, 17				
6/6/2007	18				
6/7/2007	19				
6/8/2007	20				
6/25/2007	21	*CO_2:* EGM-4, *CO:* 48C, S500, Databear	Start at < 20% RH, increase RH, let RH drop	H	B5, C5, D26-D30
6/26/2007	22				
6/27/2007	23				
6/28/2007	24				
5/31/2007	25	*O_3:* 2BTech, S500, OMC	20% relative humidity	T	B6, C6, D31-D34
6/1/2007	26				
6/29/2007	27	*CO_2:* EGM-4, *CO:* 48C, S500, Databear	Start at ~65 °F, light bulb on for 1 hr, light bulb off and bring down temp	T	B7, C7, D35-D39
7/2/2007	28				
7/3/2007	29				
7/5/2007	30				
7/6/2007	31				
4/3/2007	32,33	*CO_2:* EGM-4, Q-Trak, CO: 48C, Q-Trak	Decrease humidity while increasing temperature	T and H	B8, C8, D40-D44
4/4/2007	34	*CO_2:* EGM-4, Q-Trak, CO: 48C, Q-Trak			

[x] P = pressure, H = humidity, T = temperature

Thirty-four experiments were conducted. Table 10 shows the experimental matrix, identifying the analyzers, the environmental condition that was altered, and the numbers of the figures in the appendices containing data from each experiment. Eight experimental configurations were used: three to evaluate the effect of changing pressure, two each for the effects of changing temperature and humidity, and one to evaluate the combined effect of changing temperature and humidity simultaneously. Carbon monoxide and carbon dioxide analyzers were evaluated in the same experiments. Separate experiments were conducted with the ozone analyzers.

Appendix B contains eight figures that show the configuration of equipment in the eight chamber experiments. Appendix C contains eight pages of figures showing the time series of the chamber pressure, temperature, relative humidity and water vapor pressure during each of the 34 experiments. These figures are arranged four per page, where each page shows the temporal evolution of all four parameters during one of the eight experimental configurations. These figures reveal the extent to which one parameter was varied – for example, pressure – while the others – temperature, relative humidity and water vapor pressure – were held relatively constant throughout every experiment.

Changing Pressure: *Experiments 1-14, Figures B1-B3, C1-C3*
The analyzers were operated as pressure changed from 1.0 to 0.7 to 1.0 atm. This range is somewhat broader than the pressure range allowed in the current FAR for commercial aircraft, for which the minimum cabin pressure is 0.74 atm, a pressure altitude of 8000 ft.

Experiments began after calibration of the analyzers. Test analyzers were placed inside the chamber, the chamber lid was closed, and a vacuum pump and reference analyzers were connected to ports on the lid. Chamber pressure changed stepwise every 20 min. P decreased from 1.0 to 0.70 atm by turning on the vacuum pump and increased back to 1.0 atm by admitting air into the chamber through a valve on the lid. The temporal variation of chamber pressure is shown in Figure 8.

To maintain a steady pressure inside the chamber during each step in the profile, the sampling flow rate of the reference analyzers was varied to offset the leakage of room air into the chamber. The leak into the chamber was unintentional but convenient because it permitted gas to be drawn from the chamber without decreasing the chamber pressure. To isolate the influence of changing pressure on test analyzer performance, the humidity and temperature inside the chamber were kept relatively constant as shown in Appendix Figures B1-B3.

To isolate the reference carbon monoxide and carbon dioxide analyzers from the pressure changes of the chamber, the pumps internal to these instruments were bypassed and a variable flow peristaltic pump was placed inline between the chamber and the reference analyzers, as shown in Appendix Figures B1 and B2. The outlet ports of the reference analyzers were open to the atmosphere, and thus these instruments operated at atmospheric pressure while measuring the carbon monoxide and carbon dioxide concentrations inside the chamber.

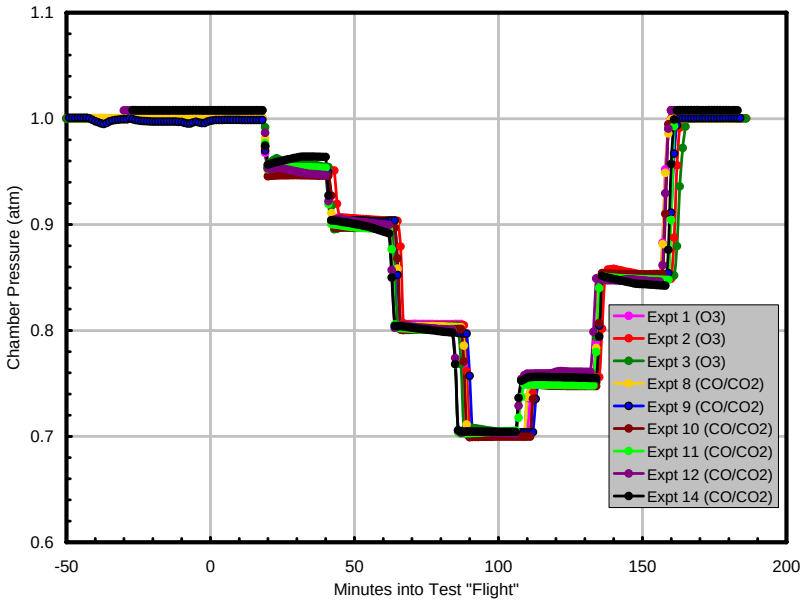


Figure 8. Pressure versus time inside the experimental chamber during experiments to evaluate ozone, carbon monoxide, and carbon dioxide analyzers. Each experiment started at t = 0 min.

The reference ozone analyzer was not isolated from the changing pressure inside the chamber. Rather, it was connected directly to the chamber with a short Teflon tube to prevent ozone loss between it and the chamber. As with the reference carbon monoxide and carbon dioxide analyzers, the pump internal to the reference ozone analyzer was bypassed in lieu of an external pump. In this case, however, the external pump was connected to the analyzer's outlet port, as illustrated in Figure B3. It was established in separate tests that the ozone concentration measured by reference ozone analyzer was unaffected by operation at reduced pressures, as shown in Figure 9. In these tests, two identical ozone analyzers were connected to the same source of ozone (~65 ppb) and the internal pressure of one of them – the analyzer used as the reference in the chamber experiments – was reduced from 1.0 to 0.7 atm while the other was operated at 1.0 atm.

In preparation for evaluating ozone analyzers in experiments 1-5, the relative humidity and ozone concentration inside the chamber were reduced to 10% and 0 ppb, respectively, by recycling air in a closed loop from the chamber through columns of charcoal and desiccant and then back into the chamber. After about 20 minutes, the recycling was discontinued, and the ozone concentration inside the chamber was increased to 60-80 ppb by injecting ozone from a corona discharge generator into the chamber and by operating a small ultraviolet lamp that was extended through a port in the chamber lid. The ozone concentration in the chamber was held approximately constant throughout the experiment, as illustrated in Figure 10, by adjusting the power supplied to the ultraviolet lamp. After a stable concentration was established, the experiment was started (i.e., at t = 0 min in Figure 8) and the pressure in the chamber was changed as described above. Temperature in the chamber at the start of these experiments ranged

from 70 to 78 °F and varied less than 5 degrees in each experiment, and relative humidity was relatively constant in the range of 20-30% (Figure C1).

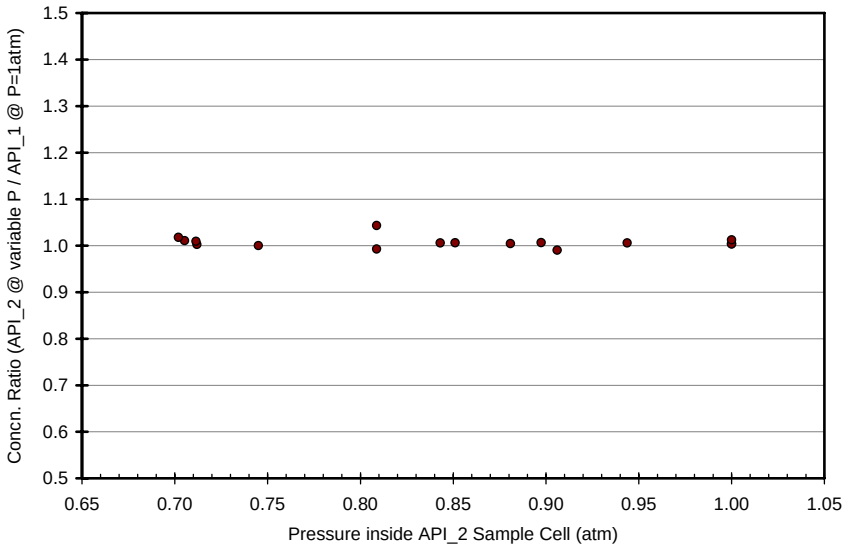


Figure 9. Ratio of ozone concentrations measured by two identical ozone analyzers (as used as the reference instrument in the chamber experiments), where one was operated at atmospheric pressure and the other was operated at pressures from 1.0 to 0.70 atm.

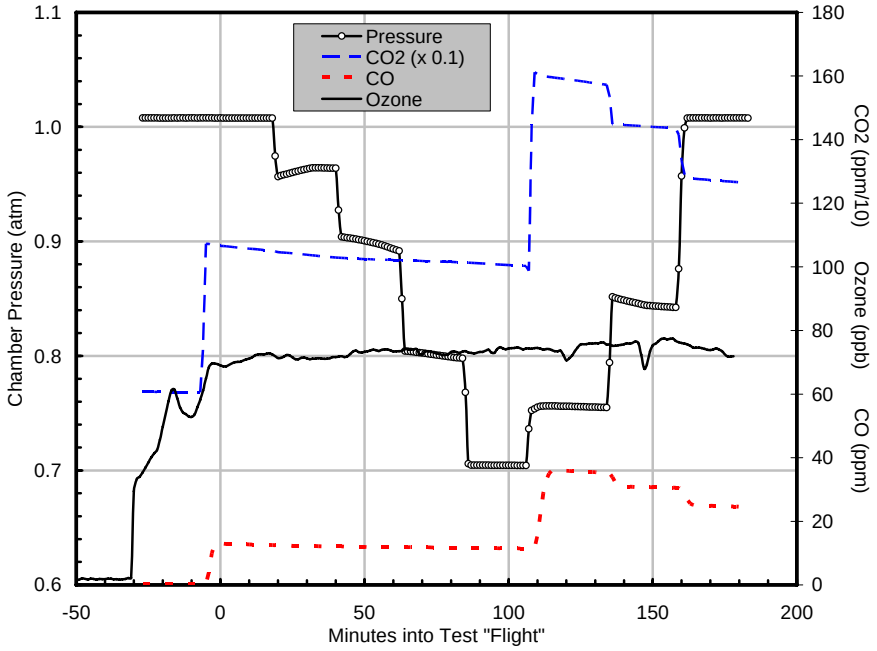


Figure 10. Typical ozone, carbon monoxide, and carbon dioxide concentrations inside the chamber during experiments, as measured by reference instruments .Ozone experiments were conducted separately from carbon monoxide/carbon dioxide experiments. The data are shown together for convenience.

Carbon monoxide and carbon dioxide analyzers were evaluated in experiments 6-14. In experiments 6-9, the relative humidity in the chamber was initially reduced to 10% (by recycling air through external desiccant, as described above), and the chamber temperature was kept between 65 and 70 ^{o}F by blowing cool air from a portable air conditioner onto the chamber exterior (Figure B2). Prior to the stepwise reduction in pressure, concentrations of carbon dioxide and carbon monoxide were increased to approximately 1500 and 30 ppm, respectively, by injecting the gases through a port in the chamber lid using a syringe. In experiments 10-14, initial relative humidity ranged from 25 to 65% (Figure C3) depending on the prevailing humidity of the room in which the chamber resided, and the chamber temperature was about five degrees warmer (70 to 75 ^{o}F) without the use of the external air conditioner (Figure C3). Prior to changing pressure, carbon dioxide and carbon monoxide concentrations were increased to approximately 1000 and 20 ppm, respectively, and in experiments 11-14, were increased by a second injection into the chamber just after increasing chamber pressure from 0.70 to 0.75 atm, as shown in Figure 10.

Changing Humidity: *Experiments 15-24, Figures B4-B5, C4-C5*

In experiments 15-20, ozone analyzers were evaluated under conditions of changing humidity. As shown in Figure 11a, the relative humidity and ozone concentration inside the chamber were initially reduced to 10-20% and 0 ppb, and ozone concentration was subsequently increased to 60-80 ppb as described above (i.e., via closed loop recycling through scrubbers and via ozone injection and operating the ultraviolet lamp extending into the chamber). Water vapor from a commercial humidifier was added to the chamber via a port in the lid to increase the relative humidity to 70-80% during these experiments (Figure B4). In half of these experiments, relative humidity was decreased to 50-60% by turning off the humidifier. To prevent ozone loss between the chamber and the reference ozone analyzer, no attempt was made to isolate the reference ozone analyzer from the changing humidity of the chamber. Rather, the reference analyzer sampled directly from the chamber via a short Teflon tube. Chamber pressure and temperature were held relatively constant, as shown in Figure C4.

Power to the ultraviolet lamp was adjusted to keep the ozone concentration in the chamber approximately constant throughout the experiment. The reference ozone analyzer, however, consistently reported widely varying ozone concentrations when relative humidity exceeded approximately 70%, as illustrated in Figure 11a. The first time this happened (in experiment 15) the power to the lamp was reduced to decrease ozone production in response to the apparent sharp increase in ozone concentration. In subsequent experiments (16-20), the lamp was not adjusted when this happened.

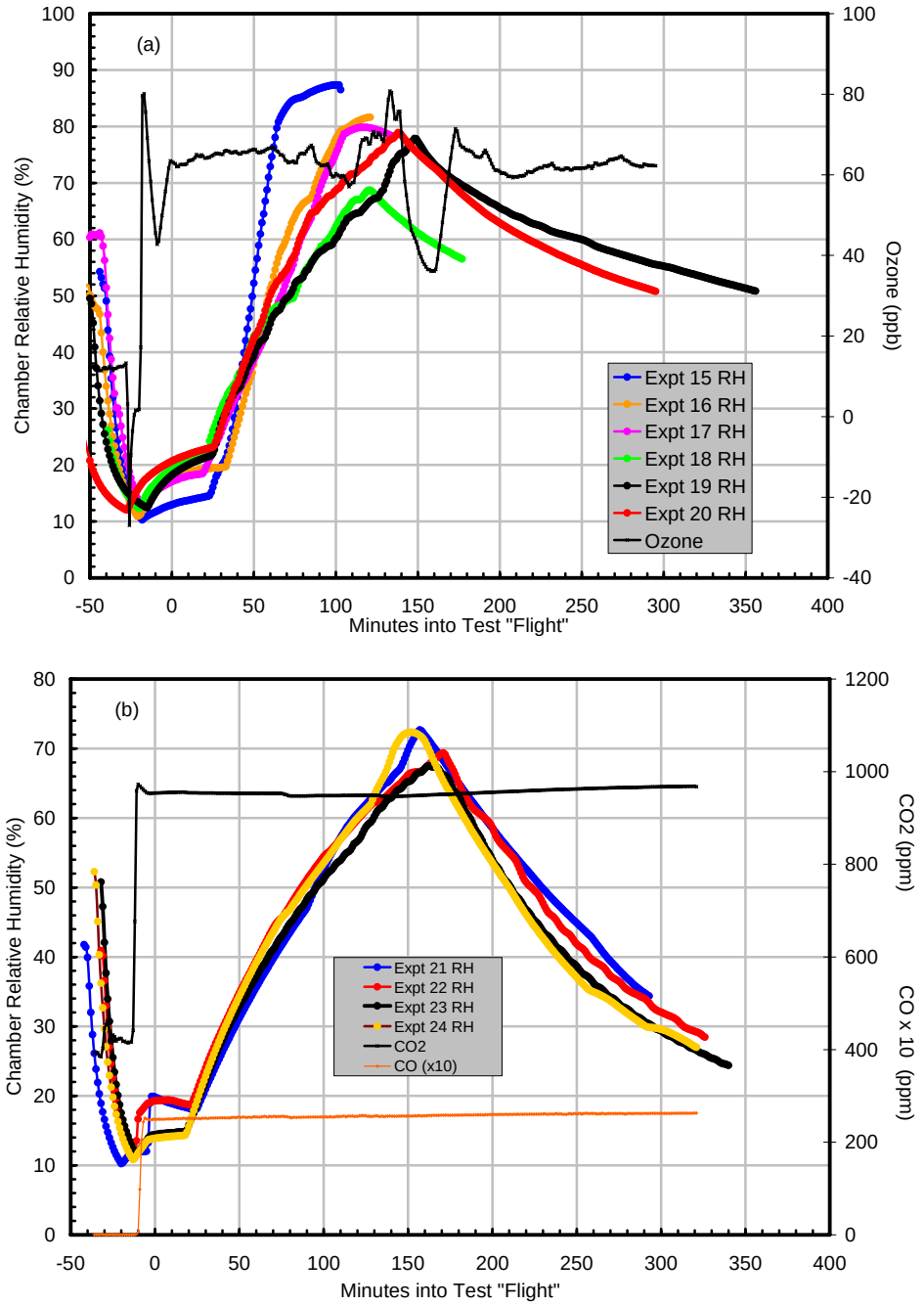


Figure 11. Relative humidity and pollutant concentrations inside the chamber versus time during experiments to evaluate the performance of (a) ozone and (b) carbon monoxide and carbon dioxide reference analyzers.

In experiments 21-24, carbon monoxide and carbon dioxide sensors were evaluated. The relative humidity inside the chamber was initially reduced to 10-20%, and then carbon dioxide and carbon monoxide concentrations were rapidly increased by syringe injection, as described above. To maintain steady concentrations of carbon dioxide and carbon

monoxide throughout these experiments, a compressed gas cylinder delivered a mixture of 1000 ppm carbon dioxide and 30 ppm carbon monoxide at 2 L/min to the chamber via a port in the lid (Figure 11b, Figure B5). After a period of stabilization, the relative humidity was increased to 70% over a period of 2 hr by passing the air from the compressed gas cylinder through a water column. Afterwards, the water column was removed and the relative humidity decreased over a period of 3 hr to 25-35% before the end of the experiments. To isolate the reference instruments from the varying relative humidity in the chamber, the sample drawn from the chamber (~ 1 L/min) was dried by passage through a column of desiccant before it was sampled, as illustrated in Figure B5.

Changing Temperature: *Experiments 25-31, Figures B6-B7, C6-C7*

In experiments 25-26 ozone analyzers were evaluated under conditions of changing temperature. As shown in Figure 12a, temperature was increased to and held at 75 ^{o}F, increased to 85 ^{o}F, and finally decreased to 65-70 ^{o}F. In experiments 27-31, carbon monoxide and carbon dioxide analyzers were evaluated. Temperature was twice cycled from 65 to 85 ^{o}F and back to 65 ^{o}F (Figure 12a). The partial pressure of water vapor (i.e., absolute humidity) and total pressure in the chamber were relatively stable during these experiments, as shown in Figures C6-C7.

At the start of each experiment the chamber interior was cooled to approximately 65-70 ^{o}F by blowing cool air from an air conditioner onto the chamber. An incandescent bulb inside the chamber, set to turn on at a predetermined time, was used to raise the chamber temperature. In experiments with ozone analyzers, the ozone concentration and relative humidity inside the chamber were initially reduced to 0 ppb and 10%, and then the ozone concentration was increased to and maintained at 60-80 ppb throughout the experiments (Figure 12a), as described above. In experiments with carbon monoxide and carbon dioxide sensors, the relative humidity inside the chamber was initially reduced to 10-20%, and then carbon dioxide and carbon monoxide concentrations were rapidly increased and maintained at 900 and 25 ppm, respectively (Figure 12b), using the methods described above. The reference ozone analyzer was isolated from the changing chamber temperature by sampling through a Teflon tube, which allowed the gas temperature to approach the temperature of the surrounding environment. A copper coil in the sampling line provided carbon monoxide and carbon dioxide reference analyzers additional isolation from chamber temperature changes. The experimental setups are shown in Figures B6 and B7.

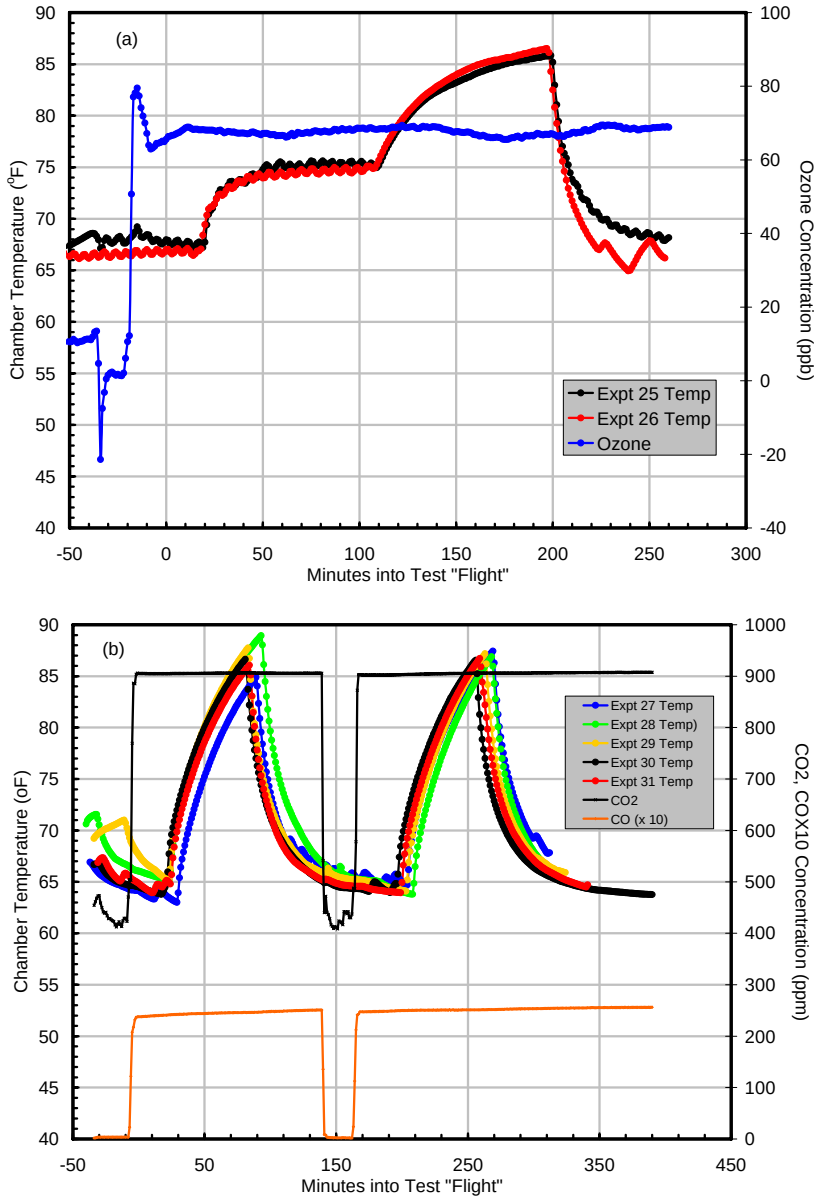


Figure 12. Temperature and pollutant concentrations inside the chamber versus time during experiments to evaluate the performance of (a) ozone and (b) carbon monoxide and carbon dioxide reference analyzers.

Changing Temperature & Humidity: *Experiments 32-34, Figures B8, C8*

In three experiments with carbon monoxide and carbon dioxide analyzers, temperature and absolute humidity were varied simultaneously, as shown in Figure C8. The relationship between temperature and humidity in experiment 34 is shown in Figure 13.

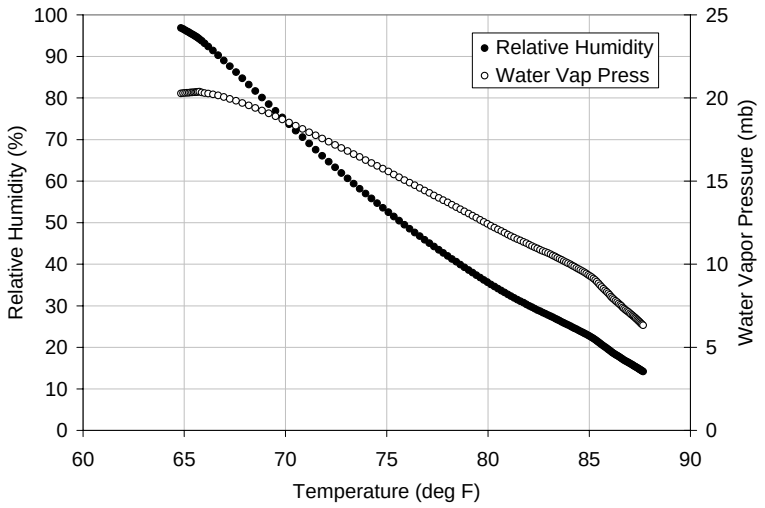


Figure 13. Plots of chamber humidity and temperature during experiment 34, where both parameters were varied simultaneously.

A humidifier was used to increase the chamber humidity prior to the start of each experiment. Carbon dioxide and carbon monoxide were injected into the chamber with a syringe, as described above, and after a brief period for stabilization, the humidity inside the chamber was reduced over a period of 2 hr by recycling air through a column of desiccant using a pump *inside* the chamber, as illustrated in Figure B8. The operation of the pump increased the chamber temperature. These experiments were conducted at a steady but reduced pressure of 0.9 atm.

Results

Calibration. Most of the test sensor systems responded linearly to increasing concentrations of calibration gases. Linear regression correlation coefficients and average slopes were close to unity, as shown in Table 11. Variability in analyzer response from one calibration to the next is expressed as the relative standard deviation of the average slope in Table 11. Notably, the heated metal oxide sensor (Aeroqual Series 500) and electrochemical cell (OMC-1108) ozone analyzers exhibited considerably more variability than the ultraviolet absorption (2B Tech Model 202) ozone analyzer. Also, the HMOS analyzer for carbon monoxide (Aeroqual Series 500) exhibited much greater variability than all other analyzers evaluated in this study. This analyzer is discussed in more detail below.

As noted above, internal calibration settings were not altered for analyzers exhibiting linear regression slopes of 1.0 ± 0.2, rather calibration data were applied to raw signals from each analyzer. There were two exceptions.

Upon receipt, the response of the OMC-1108 electrochemical ozone instrument was very low in calibration tests. The slope of the linear regression line was 0.06 and the correlation coefficient was 0.49. After consulting the supplier, the internal calibration setting was adjusted. This increased the regression slope to 0.39 and correlation coefficient to 1.0. While improving the correlation coefficient, the response remained low. The supplier subsequently tested this analyzer and reported that it responded within 10% of their reference analyzer and other sensor standards. The supplier noted the need to maintain air flow directly over the passive sensing cell. In this study, ozone analyzers were placed in a well mixed chamber during periods of calibration, as described above. Furthermore, plenty of time was given for instruments to fully respond to changes in ozone concentrations.

Table 11. Statistics derived from the calibration of the analyzers evaluated in this study; anomalous entries discussed in the text are italicized.

Analyzer	Sensor Technology	No. of Times Calibrated	Linear Correlation (r^2)	Average Slope of Regression Line[1]	RSD Slope (%)
CO Analyzers					
Langan DataBear, Model T15d	Electrochemical Cell	17	1.00	1.01	3
TSI Q-Trak Plus, 8554	Electrochemical Cell	15	1.00	1.14	4
Aeroqual Series 500	Heated Metal Oxide Sensor	4	*0.91*	*0.38*	*38*
CO_2 Analyzers					
TSI Q-Trak Plus, 8554	Non-dispersive IR absorption	15	1.00	1.05	3
PP Systems EGM-4	Spectroscopic	34	1.00	0.98	6
O_3 Analyzers					
2B Technologies, Model 202	UV absorption	4	1.00	1.02	2
Aeroqual Series 500	Heated Metal Oxide Sensor	4	1.00	*0.67*	10
OMC-1108[2]	Electrochemical Cell	3	1.00	*0.39*	7
OMC-1108[2]	Electrochemical Cell	1	*0.49*	*0.06*	-

[1] The internal calibration of the analyzers was not adjusted except in the case of the OMC-1108 ozone analyzer;
[2] The OMC-1108 was largely unresponsive to ozone upon receipt from supplier (slope = 0.06) and was, therefore, adjusted, as discussed in the text.

The response of the heated metal oxide Aeroqual Series 500 analyzer was also low. Equipped with the ozone sensor, the slope and correlation coefficient of the linear regression were 0.67 and 1.00, respectively. Equipped with the carbon monoxide sensor, the slope and correlation coefficient of the linear regression were 0.38 and 0.91. This analyzer did not allow for adjustments to internal calibration settings, so the responses could not be adjusted upwards. While the response with the ozone sensor was low, it was at least linear. The response of the carbon monoxide sensor, however, was low and non-linear: the response was especially low at low CO concentration, as shown in Figure 14. Moreover, the response of the carbon monoxide sensor was considerably more variable than the other analyzers, as indicated by the relative standard deviations of the slopes (Table 11). Because of this behavior, calibration adjustments could not applied to the data from the Aeroqual S500 carbon monoxide analyzer.

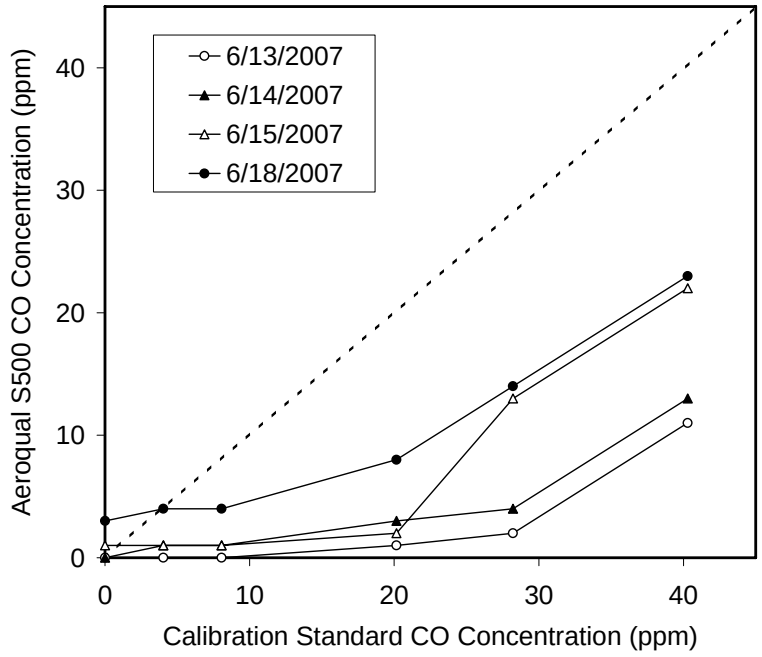


Figure 14. The nonlinear, low response of the Aeroqual Series 500 carbon monoxide analyzer during calibration tests.

Chamber Experiments. The results of the chamber experiments are shown in Appendix D. Each page in this appendix shows results for one analyzer in a set of experiments. For example, Figures D1 and D2 show the responses of the reference API ozone analyzer and the test 2BTech ozone analyzer, respectively, in experiments 1-5, which evaluated the response of analyzers to changing pressure. Each page contains multiple plots and each plot shows data from one experiment. Normalized rather than absolute pollutant concentrations are plotted. In general, the first figure in a set of experiments shows the normalized response of a reference instrument: pollutant concentrations measured throughout an experiment divided by the pollutant concentration measured at the start of

an experiment. Reference analyzer response plots illustrate the variability in pollutant concentrations during experiments. For example, the five plots in Figure D1 show how ozone concentrations varied during experiments 1-5. The figures that follow show the normalized responses of the analyzers tested in the experiments: pollutant concentrations measured by test analyzers divided by pollutant concentration measured by reference analyzers throughout experiments. Test analyzer response plots illustrate how test analyzers were affected by the changing conditions of the experimental chamber, assuming that reference analyzers were unaffected by these changes. For example, the five plots in Figure D2 show how the 2BTeach ozone analyzer responded to changing pressure in experiments 1-5.

Appendix D is arranged so that the relative performance of the different test analyzers can be observed by flipping through neighboring pages. For example, in comparing Figures D2 and D3, it is clear that the HMOS-based ozone analyzer (Aeroqual S500) was much more sensitive to changes in pressure than the UV absorption-based ozone analyzer (2BTech Model 202).

The results of the chamber experiments are discussed in the following subsections. For convenience, the names of the analyzers evaluated and their sensing technology are abbreviated, as indicated in Table 12.

Table 12. List of abbreviations used in results section of the report and its appendices.

Analyzer	Abbreviation	Sensor Technology	Abbreviation
CO Analyzers			
Langan DataBear, Model T15d	DataBear	Electrochemical Cell	EC
TSI Q-Trak Plus, 8554	QTrak	Electrochemical Cell	EC
Aeroqual Series 500	Aeroqual	Heated Metal Oxide Sensor	HMOS
CO_2 Analyzers			
TSI Q-Trak Plus, 8554	QTrak	Non-Dispersive IR Absorption	NDIR
PP Systems EGM-4	EGM4	Non-Dispersive IR Absorption	NDIR
O_3 Analyzers			
2B Technologies, Model 202	2BTech	UV absorption	UV-abs
Aeroqual Series 500	Aeroqual	Heated Metal Oxide Sensor	HMOS
OMC-1108	OMC	Electrochemical Cell	EC

Effect of Changing Pressure: Ozone analyzers: *Experiments 1-5, Figures 15, D1-D4*
Ozone concentrations generally varied by less than 20% during these experiments, as illustrated by the reference analyzer response plots shown in Figure D1. The UV absorption-based analyzer (2BTech) was consistently unaffected by pressures changes in

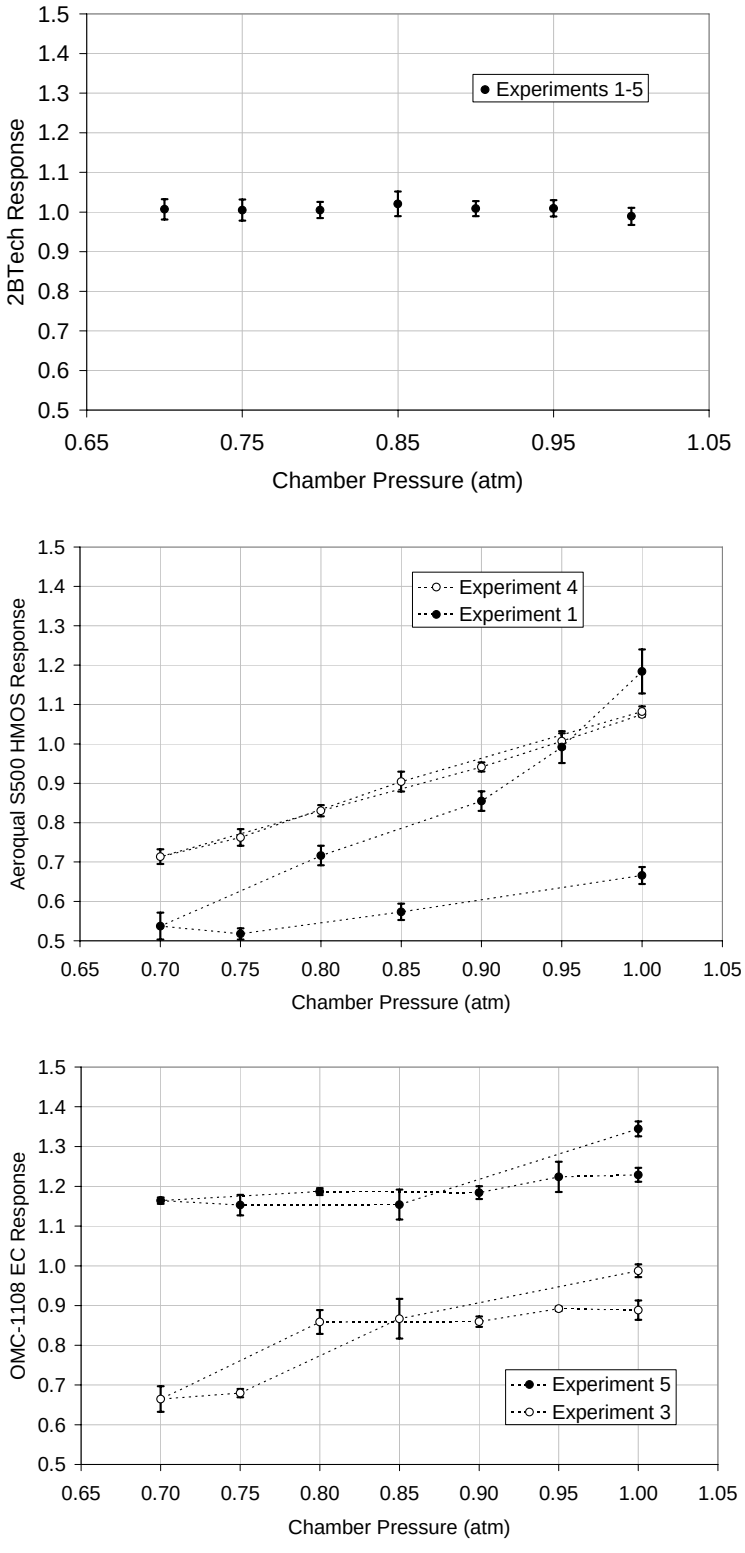


Figure 15. Response of ozone analyzers to changing pressure: *top to bottom:* (a) 2BTech UV-abs, (b) Aeroqual HMOS, and (c) OMC EC. Shown are the averages ± 1 standard deviations of data points at each pressure level in the experiments indicated.

the range considered (Figure D2). The results from experiments 1-5 have been averaged and are shown in Figure 15a. The response of the HMOS Aeroqual analyzer was not consistent in these experiments. The measured ozone concentration decreased by 30-50% as chamber pressure decreased from 1.0 to 0.7 atm (Figure D3). When chamber pressure was subsequently increased from 0.7 to 1.0 atm in experiments 1-3, the analyzer's response followed a trajectory that differed, sometimes widely, from its trajectory when pressure was decreased. The results of experiments 1 and 4, which illustrate these features, are shown in Figure 15b. The response of the EC OMC analyzer was also inconsistent in these experiments. The measured ozone concentration decreased by 10-30% as chamber pressure decreased from 1.0 to 0.7 atm (Figure D4). The results from experiments 2 and 5 are shown in Figure 15c.

The ozone concentrations measured by the Aeroqual HMOS and OMC EC analyzers differed by as much as 25% from those measured by the reference ozone analyzer at the start of some experiments when the pressure inside the chamber was 1 atm. This disparity was most likely due to variability in the calibration of these analyzers. In contrast, there was relatively little variation in the calibration of the UV-abs 2BTech analyzer (Table 11), and the UV-abs 2BTech measured ozone concentrations in close agreement with those of the reference analyzer (Figure 15a).

Effect of Changing Pressure, CO_2 Analyzers: *Experiments 6-14, Figures 16, D5-D9*
As indicated by the normalized response of the reference carbon dioxide analyzer, carbon dioxide concentrations decreased as these experiments proceeded because room air containing a relatively low carbon dioxide concentration entered the chamber via a leak during periods of decreasing pressure and via a port in the chamber lid when releasing the partial vacuum during periods of increasing pressure (Figure D5, experiments 6-9 and Figure D7, experiments 10-14). The irregular feature in experiment 7 was the result of an inadvertent deviation from the prescribed chamber pressure profile. Also evident is the step increase in response to the injection of carbon dioxide to the chamber as pressure was increased from 0.70 to 0.75 atm in experiments 11-14.

The response of both NDIR analyzers was largely consistent in these experiments (EGM4 shown in Figures D6 and D8; QTrak shown in Figure D9). Measured carbon dioxide concentrations increased approximately linearly with decreasing chamber pressure, as summarized in Figure 16. Consequently, these analyzers overstated carbon dioxide concentrations by about 6% at 0.7 atm. The sudden increases in chamber carbon dioxide concentrations in experiments 11-14 resulted in temporary decreases in the response of the QTrak analyzer (Figure D9) because its response time was slower than that of the reference carbon dioxide analyzer. These decreases were factored out in computing the average response shown in Figure 16. This was not necessary for the EGM4, which apparently had a faster response time than the QTrak (Figure D11).

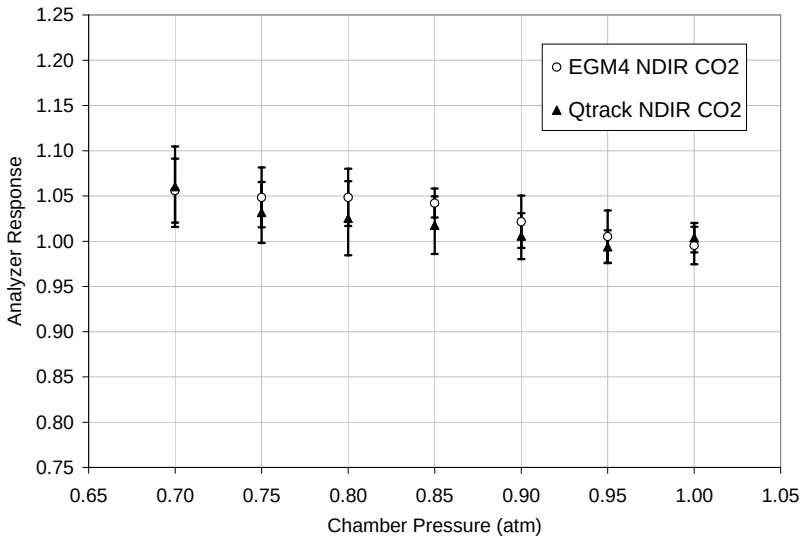


Figure 16. Responses of the EGM4 and QTrak NDIR CO_2 analyzers to changing pressure (average ± 1 standard deviation of all data points at each pressure level in all experiments).

Effect of Changing Pressure, CO analyzers: *Experiments 6-14, Figures 17, D10-D14*
Carbon monoxide concentrations during this series of experiments varied in the same manner as did carbon dioxide concentrations, as shown by the normalized response of the reference carbon monoxide analyzer (Figures D10 and D13). The QTrak EC analyzer was the least affected and the Aeroqual HMOS was the most affected by changing pressure (Figures D11, D12, and D14). The response of the QTrak was most consistent and the response of the Aeroqual HMOS was least consistent from test to test, though none of the analyzers responded consistently across all tests.

The response of the Aeroqual HMOS was typically 20% at the start of these experiments (Figure D11). As discussed above, calibration data were not applied to adjust upwards the low response of this analyzer. Its response increased as chamber pressure decreased to 0.70 atm, and then decreased along a different trajectory when chamber pressure was increased back to 1.0 atm. The pressure effect was much larger in experiments 6-8, in which the response increased from approximately 17 to 160%, than it was in experiment 9, when the analyzer response increased from 0 to 15%, as summarized in Figure 17a. The large error bars in Figure 17a are due to the substantial drift in the response of this analyzer at fixed pressures in experiments 6-8, an effect that is more apparent in Figure D11. For example, during the 20-min period when chamber pressure was maintained at 0.80 atm in experiment 6, the response increased from approximately 55 to 105% (i.e., the reported concentration of carbon monoxide doubled). These data indicated that more than 20-min were necessary for this analyzer to respond fully to the step change in pressure.

Pressure changes affected the response of the DataBear EC analyzer more in experiments 6 and 7 than in experiments 8 and 9. Figure17b includes the results of experiments 6 and 9. In particular, the difference in analyzer response to increasing and decreasing chamber

pressure was much greater in the first two experiments, where, as a result of the different trajectory, the final response was approximately 40% greater than the initial response. Not obvious in averaged data in Figure 17b, but obvious in 1-min data in Figure D12, the analyzer's immediate response to decreasing pressure was a decrease in measured carbon monoxide concentration. However, the instrument's response drifted during the 20-min periods of constant pressure – similar to the behavior of the Aeroqual HMOS but less dramatic. These competing tendencies offset each other and resulted in the saw-tooth pattern evident in Figure D12. When the data at each pressure level are averaged, the resulting trend is an increase in instrument response as pressure is increased and a larger increase in response as pressure is decreased (Figure 17b, experiment 6).

The response of the QTrak EC analyzer to the decrease in pressure from 1.0 to 0.7 atm in the first two experiments (10, 11) was a linear decrease of approximately 15% (Figure 17c). In the third experiment (13), little change in response resulted from the decrease in pressure, but a 15% increase in response resulted from the increase in pressure back to 1.0 atm. In the fourth experiment (14), the response of the analyzer increased with decreasing pressure, different than in the other three experiments (Figure D14). The peaks obvious in Figure D14 are due to the sudden injection of carbon monoxide into the chamber.

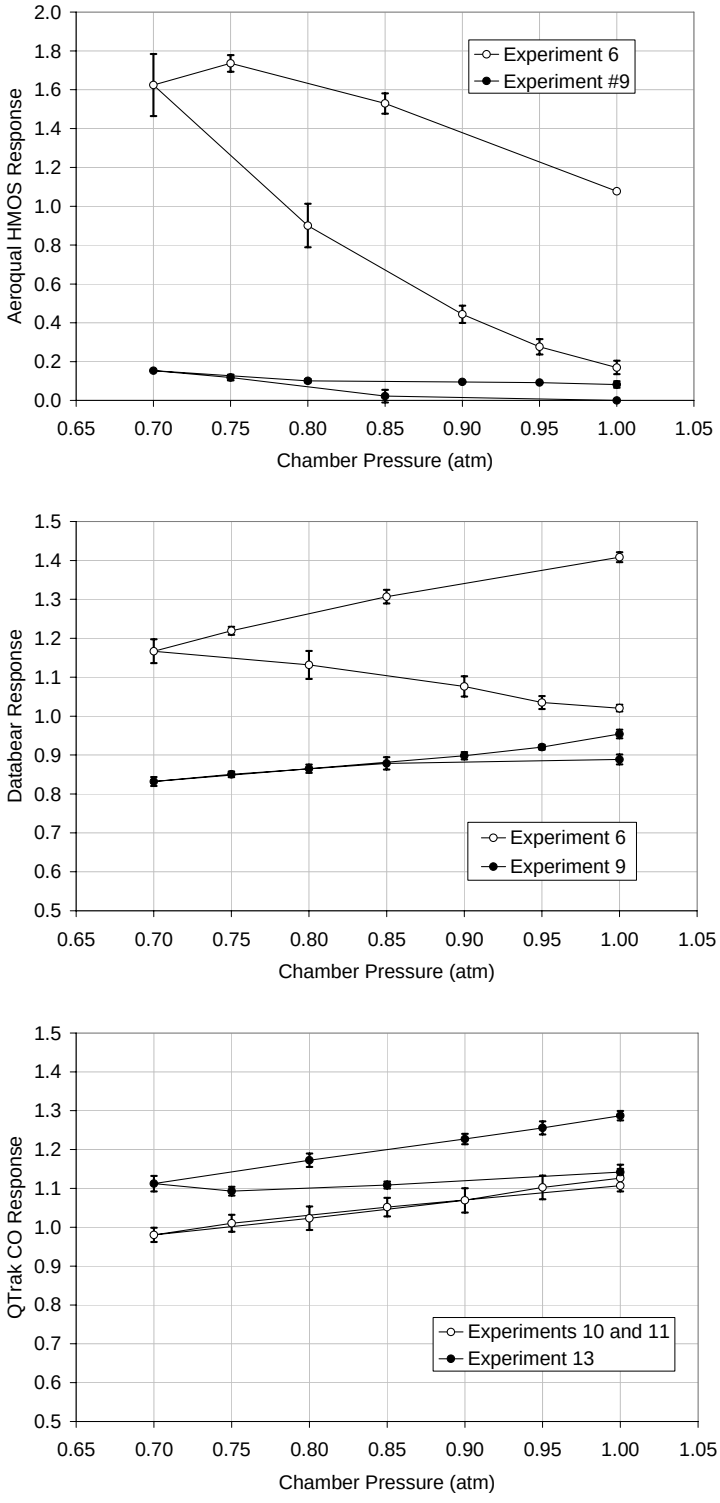


Figure 17. Response of CO analyzers to changing pressure: *top to bottom* (a) Aeroqual HMOS, (b) DataBear EC, and (c) QTrak EC. Data are shown as the averages ± 1 standard deviation at each pressure.

Effect of Changing Humidity, O_3 Analyzers: *Experiments 15-20, Figures 18, D15-D25*
The effect of changing humidity is discussed using two types of test analyzer response plots. In the first type, consistent with the plots already discussed, pollutant concentrations measured throughout experiments were divided by the concentrations measured by the reference analyzers. For example, Figure D16 reports ozone concentrations measured by the 2BTech analyzer normalized to those of the reference ozone analyzer. In the second type, similar to the reference analyzer plots already discussed, pollutant concentrations measured throughout experiments by test analyzers were divided by pollutant concentrations measured at the start of experiments by the test analyzers. For example, Figure D17 reports ozone concentrations measured by the 2BTech analyzer normalized by the concentrations reported by that analyzer at the start of each experiment. The second set of test analyzer response plots was added because the reference ozone analyzer was affected by the changing humidity in these experiments, as discussed below.

As shown in Figure D15, the response of the reference ozone analyzer indicated that relatively steady ozone concentrations were maintained in the chamber until the relative humidity reached approximately 65-75%, or a water vapor pressure of approximately 17-20 mb. (The relationship between relative and absolute humidity in these experiments is evident in Figure C4 or in a comparison of analyzer responses as a function of relative humidity in Figures D16, D18, and D20, and as a function of water vapor pressure in Figures D23-D25.) Above this humidity threshold, the reference ozone analyzer's response deviated sharply from unity. In experiments 19 and 20, when relative humidity was reduced to 50% after peaking at almost 80%, the response of the reference analyzer returned to a value of near unity. This evidence suggests that the ozone concentration in the chamber was relatively constant throughout these experiments and the reference analyzer's sharp deviation from unity was due to the erroneous behavior of the reference analyzer at high humidity.

The reference analyzer sampled directly from the chamber and no attempt was made to the reduce humidity of the sample. The erroneous behavior could have been due to the interference of water with the analyzer's ability to scrub the sample to create ozone-free air during its measurement cycle. Wilson and Birks (2006) tracked this kind of interference by water to uptake and release of water by the ozone scrubber during periods of rapid changes in humidity. Their results indicated that the water adsorbed on the cell windows and interfered with the UV transmission. A Nafion drier eliminated the problem.

Since the reference analyzer responded erroneously to relative humidity in the chamber above 65%, little can be made of the data in response plots comparing test and reference analyzers above this value. The second type of response plot, where measured ozone concentrations are normalized to initial values, are more meaningful above 65% relative humidity, though the effects of humidity on analyzer response and unintended changes in ozone concentration in the chamber would be indistinguishable. While the ozone concentration appears to have changed by less than 15% in most experiments (Figure

D15), ozone concentration was intentionally decreased at the end of experiment 15 when relative humidity was 80%. The decrease in ozone concentration at this point in experiment 15 is evident in Figures D17, D19 and D21.

In these experiments, increasing humidity affected the response of the 2BTech UV-abs analyzer (Figures D16-D17) less than the responses of the Aeroqual HMOS (Figures D18-D19) and OMC EC (Figures D20-D21) analyzers. The response of the 2BTech generally increased by 10-15% as relative humidity increased from 20% to 65%, and most of this increase occurred before relative humidity reached 40%, as shown in Figure 17a. The data in Figure C17 suggest that the 2BTech's response decreased upon further increasing humidity. On average, the response of the Aeroqual HMOS analyzer decreased linearly by 54±14% as relative humidity increased from 20% to 60% (Figure D18). This trend continued as relative humidity was further increased to 80% (Figure D19). The OMC EC analyzer generally decreased by 20% to 40% as relative humidity increased from approximately 20% to 60%. Its response was step-like and considerably less consistent that the other two analyzers from one experiment to the next.

When relative humidity was decreased to values below 60% after peaking in experiments 18-20, the response of the 2BTech UV-abs analyzer returned to its previous value (Figure C16), whereas the response of the Aeroqual HMOS (Figure D18) did not, indicating a lingering effect of the increase in humidity on the latter sensor.

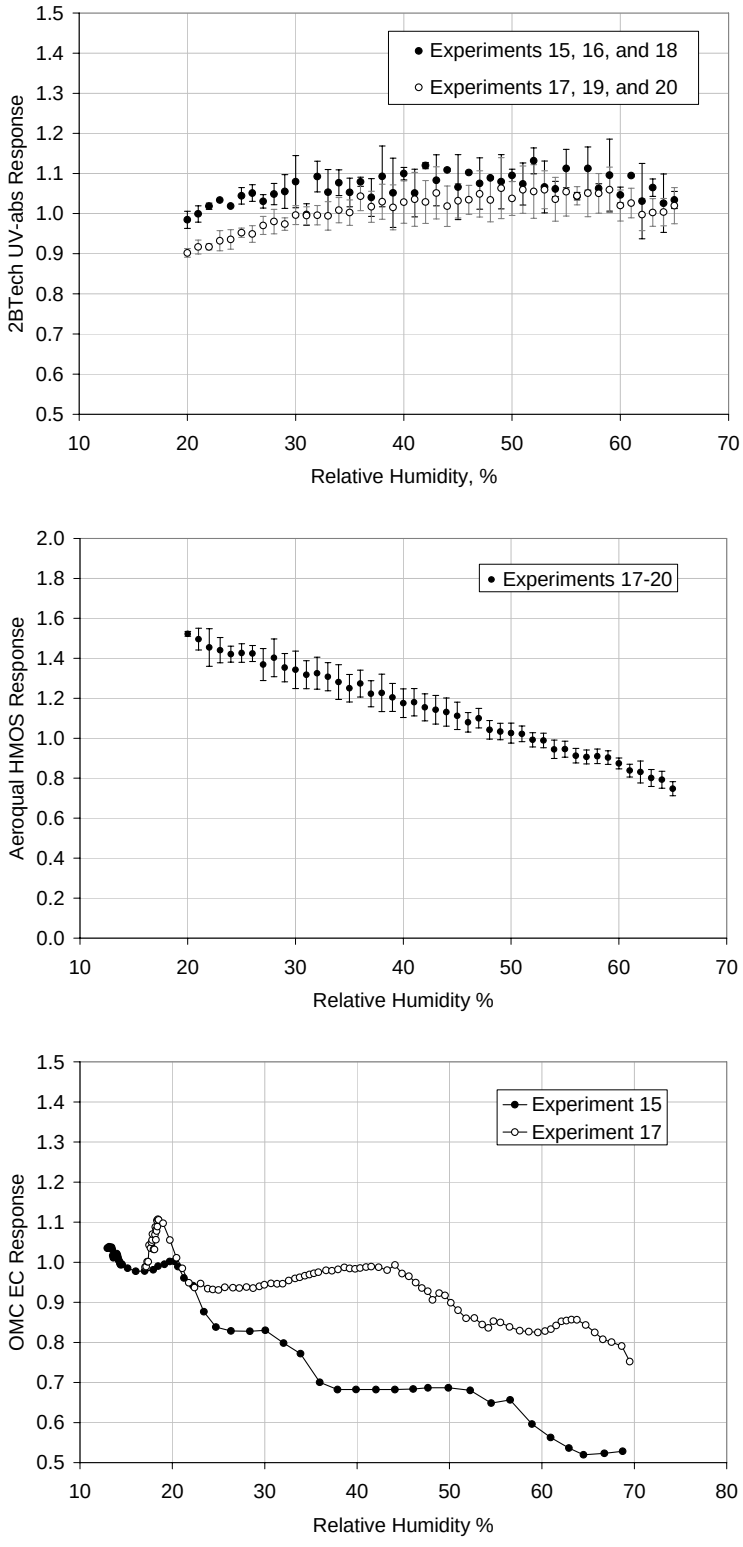


Figure 18. Response (average ± 1 standard deviation) of three ozone analyzers to increasing relative humidity in the experiments indicated: *top to bottom* (a) 2BTech UV-abs analyzer, (b) Aeroqual HMOS, and (c) OMC EC.

Effect of Changing Humidity, CO_2 Analyzers: *Experiments 21-24, Figures 19, D26-D27*
Carbon dioxide concentrations were nearly constant during these experiments (Figure D26) and the EGM4 NDIR analyzer was minimally affected by the changing humidity (Figure D27). Its response increased by approximately 2% as relative humidity increased from 20% to 70%, and the response followed the same trajectory as relative humidity was decreased. The average response from experiments 21-24 is shown in Figure 19.

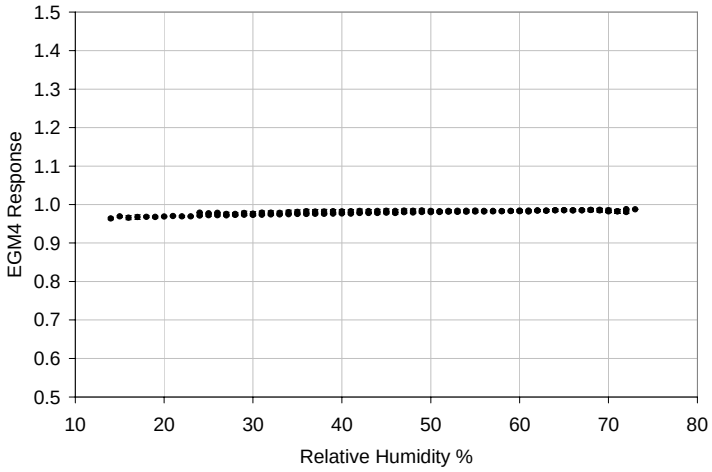


Figure 19. Average (± 1 standard deviation) response of the EGM4 NDIR carbon dioxide analyzer to changing humidity in experiments 21-24.

Effect of Changing Humidity, CO Analyzers: *Experiments 21-24, Figures 20, D28-30*
The DataBear EC analyzer was largely unaffected by changing humidity in these experiments, and the results were largely consistent from one experiment to the next (Figure D30). The average response, shown in Figure 20, decreased 3% as relative humidity increased from 15% to 72%. This analyzer's response followed the same trend during periods of both increasing and decreasing humidity.

The Aeroqual S500 HMOS was more affected by changes in relative humidity, and the response was different to increasing and decreasing relative humidity. For example, as shown in Figure 20 for experiment 23, this sensor showed essentially no response to the increase in relative humidity from 15% to 55% but an 8% increase in response with the continued increase in relative humidity from 55% to 67%. The response continued to increase another 5% as relative humidity was decreased to 40% and then began to decrease toward its initial value as humidity was further decreased. Results with this analyzer were less consistent among experiments (Figure D29) than with the electrochemical-based DataBear.

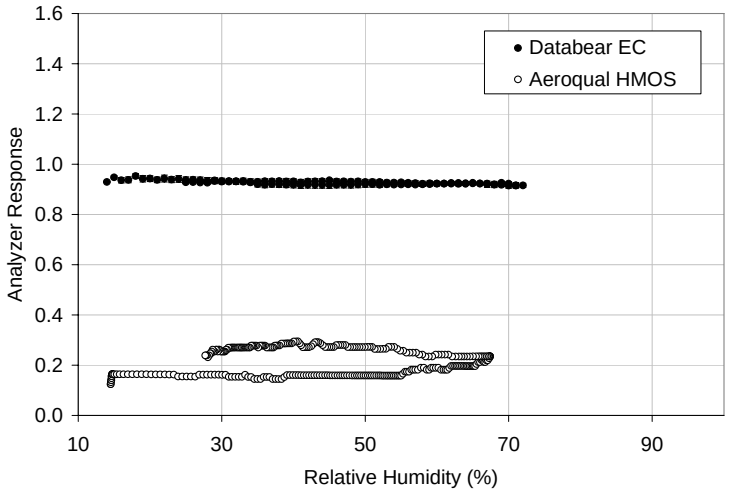


Figure 20. Response of the DataBear EC (average ± 1 standard deviation of experiments 21-24) and Aeroqual HMOS (experiment 23) CO analyzers to changing humidity.

Effect of Changing Temperature, O_3 Analyzers: *Experiments 25-26, Figures 21, D31-D34*

Figure 21 compares the responses of the three test instruments to changing temperature in experiment 26. (The outcome of experiment 25 was more or less the same for the two analyzers included.) The 2BTech UV-abs analyzer was least affected. Its response was independent of temperature between 74 and 87 ^{o}F and deviated from unity by 5% at lower temperatures.

The OMC EC and Aeroqual HMOS analyzers were appreciably affected. The OMC EC analyzer's response increased by about 15% as the chamber warmed from 67 to 75 ^{o}F but remained approximately constant after the temperature increased to 87 ^{o}F. When temperature was rapidly lowered from 87 to 65 ^{o}F, the OMC EC response decreased by

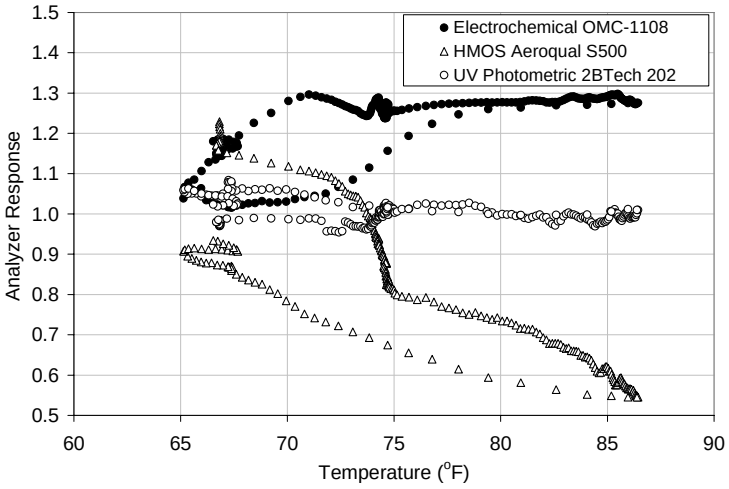


Figure 21. Response of ozone analyzers to changing temperature in experiment 26.

about 25%, though this decrease started only after the temperature had dropped by 10 ^{o}F. The overall increase in response by the EC sensor system is consistent with temperature-dependent increases in rates of both diffusion of ozone and reaction at the sensing electrode.

The response of the HMOS-based analyzer, which initially measured ozone concentrations about 15-20% in excess of the reference instrument, decreased by about 35% upon warming the chamber from 67 to 75 ^{o}F, and further decreased by 25% after warming from 75 to 87 ^{o}F. When the chamber temperature was cooled to its initial temperature, the response of the Aeroqual HMOS increased by 35% and the final response was different than the initial response. The trajectory of the response during periods of increasing and decreasing temperature was different for both the Aeroqual HMOS and OMC EC analyzers, but taken together, the HMOS response decreased as temperature increased, with degradation by hysteresis.

Effect of Changing Temperature, CO_2 Analyzers: *Experiments 27-31, Figures 22, D35-D36*

Carbon dioxide concentrations were nearly constant in each of these five experiments (Figure D35). The EGM4 NDIR analyzer was consistently unaffected by changing temperature in the 63-84 ^{o}F range (Figure D36), as illustrated by the result from experiment 27 shown in Figure 22.

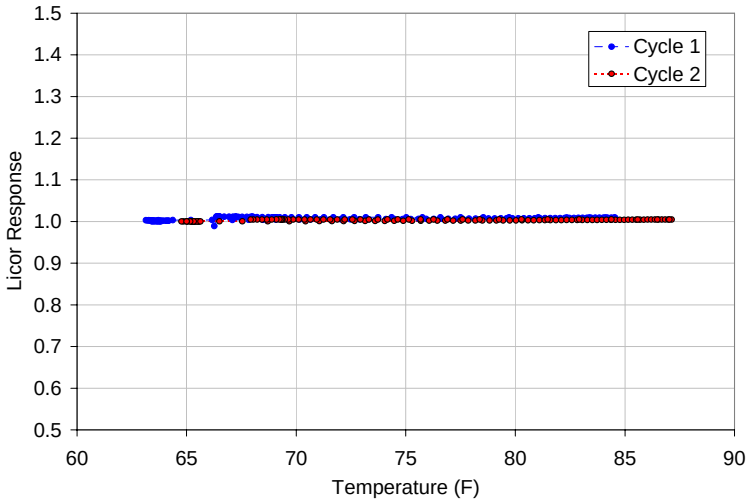


Figure 22. Response of the EGM-4 NDIR carbon dioxide analyzer in experiment 27 to the varying temperature profile shown in Figure 12b.

Effect of Changing Temperature, CO Analyzers: *Experiments 27-31, Figures 23, D37-D39*

Carbon monoxide concentrations were nearly constant in each of these five experiments (Figure D37). The tested analyzers responded similarly in each of the experiments (Figures D38 and D39). The results of experiment 27 are shown in Figure 23. The responses of both analyzers increased with increasing temperature, by about 10% for the DataBear EC analyzer and 20-25% for the Aeroqual HMOS analyzer, and returned to their initial values when the chamber temperature was restored to its initial value. In all five experiments, the DataBear EC analyzer's response was the same in the first and second temperature cycles (Figure 12b) whereas the Aeroqual HMOS responded differently to the first and second temperature cycles.

Compared to the ozone EC and HMOS analyzers, whose responses exhibited features (Figure 21) that appeared to be linked to the rate of temperature change (Figure 12), the CO EC and HMOS analyzer responses appeared less sensitive to the dynamics of the temperature profile.

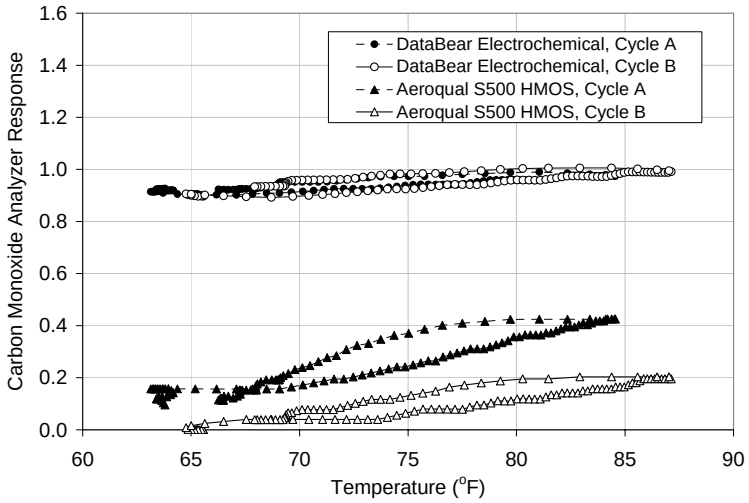


Figure 23. Response of two CO analyzers in experiment 27 to changing temperature.

Effects of Changing Humidity and Temperature Simultaneously: CO_2 and CO Analyzers: *Experiments 32-34, Figures D40-D44*

Carbon dioxide concentrations were maintained approximately constant during these experiments. The analyzer responded to the changing chamber conditions, as shown in Figure 24 for experiment 34. Since two parameters changed simultaneously, it was not clear which parameter most affected the instrument's response. The slight decrease measured by the reference analyzer (Figure D40) was due to the leakage of ambient air into the chamber. Both NDIR analyzers showed essentially no response (< 2% increase) to the simultaneous large reduction in humidity and increase in temperature (Figures D41-42), as shown in Figure 24 for experiment 34.

Carbon monoxide concentrations inside the chamber decreased to a greater extent than did carbon dioxide concentrations in these experiments (Figure D43) because the ambient air that leaked into the chamber was essentially free of carbon monoxide.

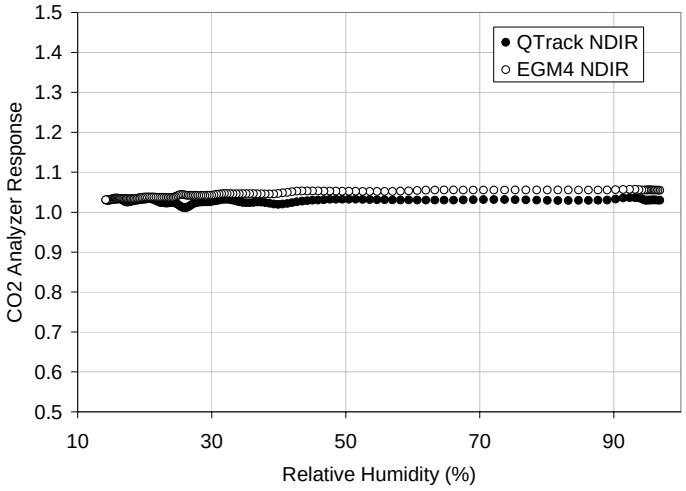


Figure 24. Response of two NDIR carbon dioxide analyzers to simultaneously decreasing humidity and increasing temperature in experiment 34. Analyzer response is plotted versus humidity only. The relationship between humidity and temperature is shown in Figure 13.

For the sake of comparison, the response of the other EC analyzer evaluated in this study, the DataBear, to separately changing humidity and temperature in experiments 23 and 27, respectively, is shown in Figure 25. The DataBear was more affected by temperature than humidity, and the slope of its response was similar to the slope of the QTrak's response between 70 and 80 ^{o}F. The increase in the QTrak's response outside of this temperature range was not reflected in the DataBear's response.

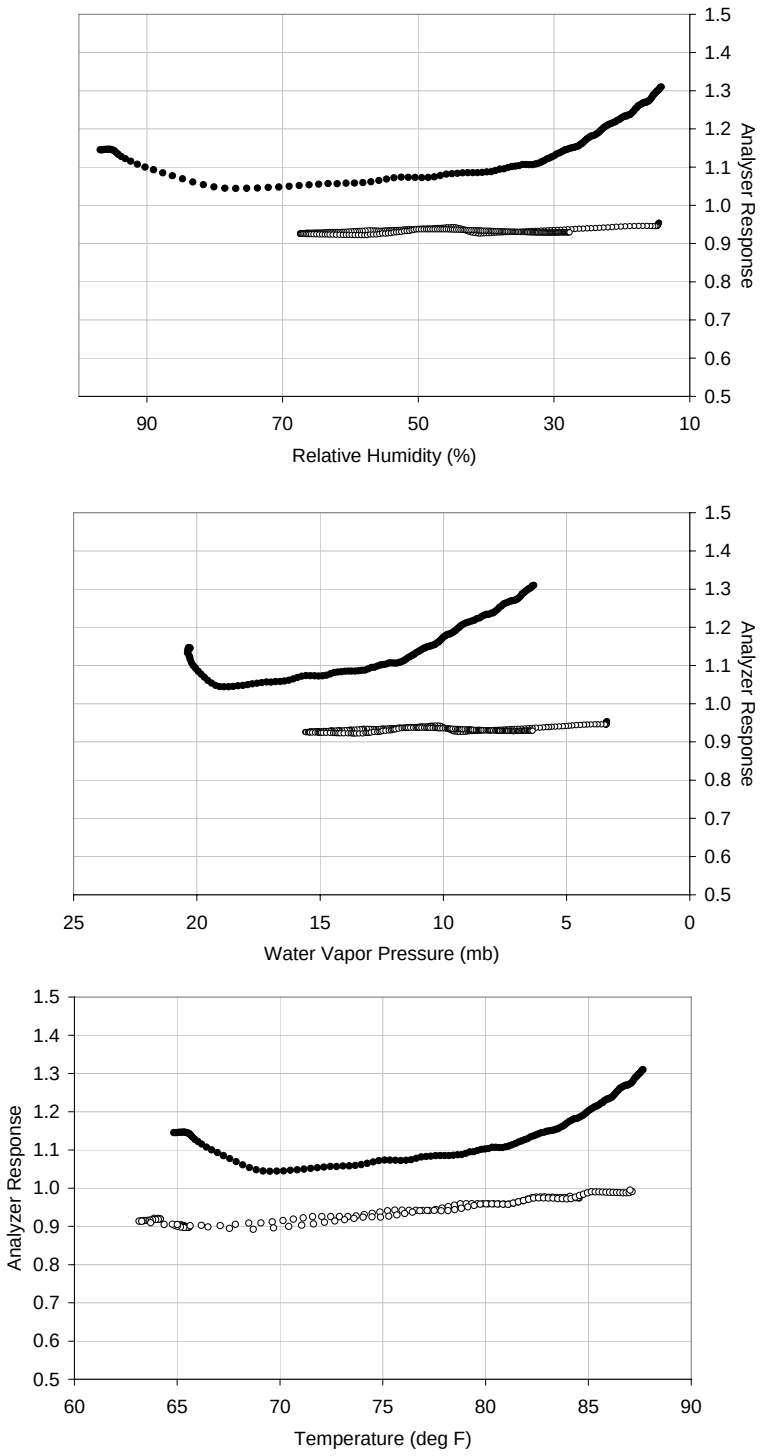


Figure 25. Response of the QTrak EC carbon monoxide analyzer (●) in experiment 34 to simultaneously decreasing humidity and increasing temperature. Analyzer response is plotted *top to bottom* versus (a) relative humidity, (b) water vapor pressure, and (c) temperature. Also shown is the response of the DataBear EC analyzer (○) to separately changing humidity in experiment 23 and temperature in experiment 27.

Summary of Chamber Experiments

The results of the pressure, humidity, and temperature experiments are summarized in Tables 13, 14, and 15, respectively. In addition to comparing the magnitudes of the responses of the different analyzers subjected to changing environmental conditions, these tables also indicate whether or not the responses were consistent in a manner suggesting that an algorithm could be used to adjust the responses to generate accurate measurements of pollutant concentrations. An analyzer whose response depends on the aircraft environment may be acceptable provided the dependence is predictable. In this study, a response was deemed predictable if it was consistent from one experiment to the next and it was approximately the same when the chamber pressure, humidity, or temperature was increasing or decreasing.

Of the ozone analyzers evaluated, the UV-absorption (2BTech 202) analyzer performed best. Its response was consistent from one experiment to the next, changing pressure and temperature had little impact on its response, changing humidity impacted its response (only at RH outside of the range occurring in-flight) in a consistent manner, and it responded consistently during calibrations. The ozone analyzers with the electrochemical cell (OMC-1108) and heated metal oxide sensor (Aeroqual S500) exhibited large responses to changing pressure, humidity and temperature that, with exception of the response of the heated metal oxide sensor to changing humidity, were unpredictable, and their responses were far below unity and more variable than the response of UV-absorption-based analyzer during calibrations.

The two NDIR carbon dioxide analyzers (TSI Q-Trak Plus, 8554 and PP Systems, EGM4) performed very well. Their response was consistent from one experiment to the next, changing temperature and humidity had little or no impact on their response, changing pressure from 1.0 to 0.7 atm increased their response by a predictable 6%, and they responded consistently during calibrations.

Changing pressure had a large impact on each of the carbon monoxide analyzers, and none of the analyzers responded in a predictable enough manner to meet requirements for accuracy. The two electrochemical cell-based analyzers (Langan DataBear T15d and TSI Q-Trak Plus 8554) responded consistently and linearly during calibrations; however, unlike the two carbon dioxide analyzers with the same (NDIR) technology, these two electrochemical cell-based analyzers did not respond similarly to environmental conditions. Both responded predictably to changing humidity, but the magnitude of the humidity effect on the response of the DataBear was small and the Q-Trak Plus was large. Both responded predictably to changing temperature, but the magnitude of the effect was moderate for the DataBear and large for the Q-Trak Plus. Of the carbon monoxide analyzers evaluated, the heated metal oxide sensor (Aeroqual S500) performed poorest. Both changing pressure and changing temperature had large impacts on its response. Changing humidity had a moderate but unpredictable impact, and it responded nonlinearly and inconsistently during calibrations.

Table 13. Summary of how changing pressure (from 1.0 to 0.70 to 1.0 atm)[1] affected analyzer response.

Analyzer	Sensing Technology	Maximum Change in Analyzer Response[2]			Predictable Response[3]
		< 5%	5 to 15%	> 15%	
CO Analyzers					
Langan DataBear, T15d	Electrochemical Cell			Decrease	No
TSI Q-Trak Plus, 8554	Electrochemical Cell			Decrease	No
Aeroqual S500	HMOS			Increase	No
CO_2 Analyzers					
TSI Q-Trak Plus, 8554	NDIR		6% Increase		Yes
PP Systems, EGM4	NDIR		6% Increase		Yes
O_3 Analyzers					
2B Tech, 202	UV-abs	Little or No Effect			Yes
Aeroqual S500	HMOS			Decrease	No
OMC-1108	Electrochemical Cell			Decrease	No

[1] The pressure profile is shown in Figure 8.
[2] The indicated response (increase or decrease) is with respect to a decrease in pressure.
[3] "Yes" means that the response of the analyzer was consistent from one experiment to the next in a manner suggesting that an algorithm could be used to compensate for the effect of pressure on the analyzer's response.

Table 14. Summary of how changing relative humidity (from 20 to 65%)[3] affected analyzer response.

Analyzer	Sensing Technology	Maximum Change in Analyzer Response[1]			Predictable Response[2]
		< 5%	5 to 15%	> 15%	
CO Analyzers					
Langan DataBear, T15d	Electrochemical Cell	2% Decrease			Yes
TSI Q-Trak Plus[3,4], 8554	Electrochemical Cell			X	Yes
Aeroqual S500	HMOS		X		No
CO_2 Analyzers[4]					
TSI Q-Trak Plus, 8554	NDIR	Little or No Effect			Yes
PP Systems, EGM4	NDIR	Little or No Effect			Yes
O_3 Analyzers					
2B Tech, 202[5]	UV-abs		Increase		Yes
Aeroqual S500	HMOS			Decrease	Yes
OMC-1108	Electrochemical Cell			Decrease	No

[1] The indicated response (increase or decrease) is with respect to an increase in humidity. An "X" means the direction of the response was inconsistent.

[2] "Yes" means that the response of the analyzer was consistent from one experiment to the next in a manner suggesting that an algorithm could be used to compensate for the effect of humidity on the analyzer's response.

[3] The TSI QTrak was evaluated as temperature and humidity changed simultaneously; the response indicated here may be due to either or both, changing temperature and changing humidity.

[4] The two carbon dioxide analyzers and the QTrak carbon monoxide analyzer were evaluated over a 15% to 95% relative humidity range.

[5] The 2B Tech 202 was independent of relative humidity up to 60-65%.

Table 15. Summary of how changing temperature (from 65 to 85 to 65 ^{o}F) affected analyzer response.

Analyzer	Sensing Technology	Maximum Change in Analyzer Response[1]			Predictable Response[2]
		< 5%	5 to 15%	> 15%	
CO Analyzers					
Langan DataBear, T15d	Electrochemical Cell		Increase		Yes
TSI Q-Trak Plus[3], 8554	Electrochemical Cell			X	Yes
Aeroqual S500	HMOS			Increase	No
CO_2 Analyzers					
TSI Q-Trak Plus, 8554	NDIR	No Effect			Yes
PP Systems, EGM4	NDIR	No Effect			Yes
O_3 Analyzers					
2B Tech, 202	UV-abs	X			Yes
Aeroqual S500	HMOS			Decrease	No
OMC-1108	Electrochemical Cell			Increase	No

[1] The indicated response (increase or decrease) is with respect to an increase in temperature. An "X" means the direction of the response was inconsistent.

[2] "Yes" means that the response of the analyzer was consistent from one experiment to the next in a manner suggesting that an algorithm could be used to compensate for the effect of temperature on the analyzer's response.

[3] The TSI QTrak was evaluated as temperature and humidity changed simultaneously. The response was evaluated for increasing temperature only. The response indicated here may be due to either or both of changing temperature and humidity.

Comparison of the performance of COTS sensors to benchmarks and requirements for use in aircraft

Ozone. The three tables that follow show the suitability of these COTS sensor systems for monitoring ACEQ, based on whether or not each of the representative sensors met the technical criteria shown in Table 6. Tables 16-18 compare the sensing technologies pollutant by pollutant. The outcomes for accuracy and sensor size are highlighted in bold face to emphasize their crucial importance. In these tables the criterion for the effect of humidity has been displayed in two ranges: 10-30% and 10-65% RH. The shorter humidity range is appropriate in flight, and the longer range applies to operation on the ground with outdoor air supplying the cabin.

Table 16. Ozone: Performance of commercially available sensors compared to the requirements for monitoring ACEQ. S and U stand for satisfactory and unsatisfactory, respectively.

Ozone			
Characteristic	**UV Absorption**	**EC**	**HMOS**
Accuracy ±15%	**S**	**U**	**U**
Pressure (0.7-1 atm)	S	U	U
Humidity (10-30% RH)	S	U	U
Humidity (10-65% RH)	S[1]	U	U
Temperature (65-85 °F)	S	U	U
Sensitivity (low ambient)	S	S	S
Sampling frequency (1 min^{-1})	S	S	S
Response time (< 1 min)	S	U	S
Size (sensing element ≤ 1 cm diameter)	**U**	**S**	**S**
Power (28 V)	S	S	S
Weight (≤ 1 kg with electronics)	U	S	S
Cost	U	U	U

[1]Water sensitivity over 65% RH.

Table 16 shows that neither of the COTS chemical sensors (EC, HMOS) monitored ozone accurately (±15%) under the range of environmental conditions that occur in aircraft cabins. The accuracy criteria were not met for variation in pressure, humidity or temperature. Because both types of chemical sensors are dependent on ambient oxygen, the observed overall trends of their dependence on cabin pressure were consistent with the expected behavior, but substantial hysteresis and poor reproducibility also degraded accuracy for both. The monitor that quantified ozone by absorption of ultraviolet light met the criteria for accuracy in every category, but its sensing components were too large for installation in or near ports in the air supply manifold. As packaged the ozone analyzer was also too heavy.

On the horizon, small ozone sensors have been developed using nanostructured alumina, nanoporous ceramic membranes, and solid polymer electrolytes (Appendix A1.34-A1.37). The continuing effort to develop improved metal oxide-based sensors for ozone is reflected in the ten peer-reviewed publications, mostly from academic institutions, that are mentioned in Appendix A1 (references A1.40 to A1.49).

Carbon dioxide. For CO_2 the most widely used sensing technology in COTS analyzers is based on non-dispersive infrared absorption, as shown in Appendix A4. The two representative NDIR analyzers worked very well for real-time monitoring under environmental conditions that occur in aircraft cabins, as Table 17 indicates. The sensor elements for both of the instruments were too large (> 1 cm diameter) because current designs have not achieved adequate sensitivity over a sufficiently short optical path. The sensor survey also identified COTS sensors based on the properties of carbon nanotubes, electrochemical cells, or photoacoustics (references A4.1, A4.2 and A4.40, respectively). However, these systems appeared to be unlikely to meet enough of the screening criteria for laboratory testing. The results of this study show that NDIR sensor elements need to be miniaturized, and/or other types of sensors need to be improved for routine use onboard aircraft. The sensor survey did reveal that a MEMS-based infrared sensor is on the horizon (references A4.41-A4.43), but it is not yet sensitive enough. In the long term, current research may lead to suitable CO_2 sensor systems based on carbon nanotubes, electrochemical cells or improved metal oxides (references A4.44-A4.47).

Table 17. Carbon Dioxide: Performance of commercially available sensors compared to the requirements for monitoring ACEQ. S and U stand for satisfactory and unsatisfactory, respectively.

Carbon Dioxide	S	
Characteristic	**NDIR: Q-Trak**	**NDIR: EGM4**
Accuracy ±15%	**S**	**S**
Pressure (0.7-1 atm)	S	S
Humidity (10-30% RH)	S	S
Humidity (10-65% RH)	S	S
Temperature (65-85 °F)	S	S
Sensitivity (low ambient)	S	S
Sampling frequency (1 min^{-1})	S	S
Response time (<1 min)	S	S
Size (sensing element ≤ 1 cm diameter)	**U**	**U**
Power (28 V)		
Weight (≤ 1 kg with electronics)	S	S
Cost	U	U

Carbon monoxide. The small size of typical COTS chemical sensors for CO makes them attractive candidates for monitoring ACEQ. However, laboratory testing found that neither type of the chemical sensor for carbon monoxide (electrochemical or heated metal oxide semiconductor) met the accuracy criteria, as summarized in Table 18. Neither type responded accurately enough as the pressure was lowered to 0.7 atm and then returned to sea-level pressure. Both instruments with electrochemical cells met the humidity and temperature criteria, but the HMOS sensor system did not. The general trend in response of the HMOS sensor to changes in humidity was obscured by substantial hysteresis. However, with improvements in control of hysteresis and reproducibility, HMOS sensors would meet the criterion for response to CO during changes in temperature.

On the near-term horizon are new EC and MOS sensors that take advantage of advances in nanoscale material science and microelectromechanical engineering (Appendix A3, references A3.38 and A3.39, respectively). Research reports suggest that suitably sized CO sensors may be available in the long term, based on the electronic properties of carbon nanotubes (references A3.40-A3.43), coated porous silicon (A3.44), IR absorption at 865 nm (A3.45) and/or improved MOS structures (A3.46).

Table 18. Carbon Monoxide: Performance of commercially available sensors compared to the requirements for monitoring ACEQ. S and U stand for satisfactory and unsatisfactory, respectively.

Carbon Monoxide			
Characteristic	**EC: DataBear**	**EC: Q-Trak**	**HMOS**
Accuracy ±15%	**U**	**U**	**U**
Pressure (0.7-1 atm)	U	U	U
Humidity (10-30% RH)	S	S[1]	U
Humidity (10-65% RH)	S	S[1]	U
Temperature (65-85 °F)	S	S[1]	U[2]
Sensitivity (low ambient)	S	S	S
Sampling frequency (1 min^{-1})	S	S	S
Response time (< 1 min)	S	S	U
Size (sensing element ≤ 1 cm diameter)	**S**	**S**	**S**
Power (28 V)	S	S	?
Weight (≤ 1 kg with electronics)	S	S	S
Cost	U	U	U

[1]See footnotes 3 and 4 of Table 14.
[2]Response increased linearly with increasing T; compensation may be possible.

PART III. SUMMARY, DISCUSSION AND RECOMMENDATIONS

Recommendations for sensor monitoring of ACEQ (Task 5) follow a summary of the findings of Parts I and II. The summary is presented as progress toward achieving the specific aims that were listed in the Introduction.

Summary: Progress towards achievement of specific aims

1a) Identification of aircraft cabin environmental quality concerns for which sensors may be useful

The highest priority environmental indicators identified are ozone and cabin air pressure, followed by carbon monoxide and carbon dioxide with moderate priority, and then relative humidity, airborne particles, and organic contaminants, including engine oil byproducts and pesticides. This list is based on the Congressional requirements and scientific literature, starting with information from recent studies (NAS/NRC, ASHRAE/Battelle), and continuing by seeking input from a variety of stakeholders.

The parameters that can be monitored routinely with **off-the-shelf sensor technology are ozone, cabin pressure, CO, CO_2 and relative humidity. These formed the prioritized list of environmental parameters for in-flight sensing.**

1b) Definition of requirements for sensors and sensor systems

LBNL investigators deduced that sensors intended to provide data for routine use by stakeholders must emphasize **simplicity, ruggedness and satisfactory performance with limited attention by the crew and maintenance staff.** In order to guide maintenance of environmental control systems and document exposure to contaminants, sensors should be installed at multiple locations in the bleed air and cabin air supply/recirculation system, including the return duct. Packaging requirements for installation and operation on aircraft emphasize simplicity, ruggedness and satisfactory performance with limited attention by the crew and maintenance staff. Within these limits:

i. *Specific requirements* or benchmarks for performance emphasize **accuracy (±15%), sensitivity (low ambient), and sampling interval (≤ 1 min)**.
ii. *Suggested requirements* include limitations on the size of sensor elements (≤ 3/8 in diameter), weight of sensor systems (≤ 1 kg), power (28 V), frequency of maintenance (coincident with service schedules), required operator skill (minimal) and target cost for replaceable sensor elements (≤ $100).

2) Sensor systems most capable of meeting current requirements.

A survey of sensor systems, parameter by parameter, from highest priority to lowest, is included as Appendix A. Systems chosen for testing were based on principles that are representative of the main approaches that are utilized currently for **real-time monitoring of the prioritized parameters**. The use of **COTS systems** simplified the

experimental approach because data from their sensors could be acquired without the requirement of project staff designing and building prototype units. However, no COTS system met all the specifications or benchmarks. To proceed under this limitation, sensors judged to be most capable of meeting requirements were tested in COTS systems based on IR or UV spectroscopy, electrochemical cells, and metal oxide semiconductors. The selected technologies were based on light absorption (UV for ozone and non-dispersive IR for carbon dioxide) and electrochemistry (electrochemical cells and metal oxide semiconductors for ozone and carbon monoxide). Pressure sensors are already standard in aircraft, although the output needs to be logged.

3) Performance of sensors

Representative sensor technologies were tested as COTS systems in the laboratory under conditions that occur in-flight (cabin air pressure 0.7 to 1 atm; temperature from 65 to 85 °F) and at ground level (relative humidity from 20% to 80%). The sensor systems were challenged with ozone, carbon monoxide and carbon dioxide. However, no tests were performed with simultaneous challenges by ozone, CO, CO_2. The sensor systems were not evaluated in the presence of contaminants such as pesticides, ethanol, VOCs (ethanol, toluene, unsaturated hydrocarbons) or pyrolysis products (hydraulic fluids, lubricants and fuel additives), nor were they subjected levels of vibration that occur on aircraft.

The results show that **neither the EC nor MOS-based sensors responded with at least ±15% accuracy**, primarily due to poor reproducibility and hysteresis. **The sensors based on light absorption (UV for ozone and IR for CO_2) performed better under the influence of changes in pressure, temperature and humidity than did the sensors that depend on electrochemistry (for ozone and CO, analyte-induced redox reactions at sensing and counting electrodes (EC) or at the gas-sensing surface of the (HMOS sensor))**. The UV-based sensor gave unacceptable performance (> 15% change) only when the relative humidity exceeded 65%, but this condition does not occur commonly in flight where RH rarely exceeds 30%. Furthermore, a solution to this problem exists: Wilson and Birks (2006) have shown recently that this interference can be minimized with a scrubber for water vapor that does not influence the ozone concentration. Nevertheless, **the optical sensors, both UV and NDIR, need further miniaturization** before they can be installed routinely in aircraft.

4) Recommendations for sensor development and testing (see next section, Task 5, below)

Task 5: Additional sensor development needs and testing plans

The responses of representative sensors revealed that further development of sensor technologies is necessary to meet the criteria described in Tables 5 and 6.

Recommendations for sensor development

The performance (poor reproducibility and significant hysteresis) of the EC and HMOS-based sensors is disappointing because their compact size would otherwise allow them to be installed in aircraft without extensive redesign. The number of such sensors tested in this study is too small for the results to be predictive of the performance of the wide variety of EC and MOS-based sensors that are used in current COTS.

The sensing materials in both EC and MOS sensors depend on interfacial reactions involving ambient oxygen, as well as interactions with the target gas, and water vapor is known to interfere with many chemical sensors. There is considerable potential for developers to tailor the composition and properties of the sensors' gas-sensitive materials to optimize their performance under conditions of changing pressure, temperature and relative humidity. A near-term performance milestone is achieving reproducible and predictable responses to the changes in pressure, temperature and humidity that occur in-flight. Then developers can implement compensation algorithms for sensor dependence on these characteristics.

Suggestions for encouraging sensor development include:

- Circulating the main findings of this study among sensor manufacturers to stimulate development of improved technologies for aircraft ACEQ.
- Implementing ASHRAE's recommendations for routine monitoring to encourage aircraft-specific sensor designs. When large markets exist for monitoring ACEQ, developers and manufacturers will have more incentive to miniaturize optical sensors (for example, by using LEDs as light sources) and tailor materials for EC, MOS and other to meet the performance specifications. Costs could approach the benchmark of ≤ $100 per sensor element. (Current EC and MOS sensor elements cost at least twice the target amount.)

Recommendations for future sensor testing

- Broaden the usefulness of the results by evaluating the performance of a larger selection of existing sensors, including GOTS and promising sensors in the research phase. Doing so would provide stronger guidance for both sensor development and industry-wide monitoring of ACEQ.
- Evaluate the performance of improved sensor materials and assess the performance of systems that become candidates for widespread use in aircraft. A body such as an ASHRAE committee of stakeholders and sensor developers could use this report's protocols as a starting point for evaluating improved sensors.

- Use the protocols presented here to screen sensor systems before more rigorous testing intended to overcome the limitations identified in this study.
- Test sensor systems for cross-sensitivity of ozone and CO; then add common VOCs found on aircraft (toluene, terpenes, ethanol) and halogen-containing species (pesticides and flame retardants).
- Evaluate the viability of using CO/CO2 ratios to signal incidents caused by pyrolysis products.
- Collaborate with aircraft engineers for in-flight testing of the best available sensor technologies.

Conclusions from evaluation of representative sensor systems

- The optical sensor elements were sufficiently accurate, but too large for installation at multiple locations in the air supply system.
- The EC and HMOS sensors were inaccurate, although appropriately-sized and widely available.
- None of the tested sensors would be well suited for widespread deployment for routine monitoring of ACEQ in the near term.
- Testing revealed a great need for compact, accurate sensors for ozone, the highest priority parameter for monitoring aircraft cabin environmental quality.
- Although optical sensors performed better than chemical sensors for ozone and CO, optical sensors need to be miniaturized so that they can be installed at multiple locations in the aircraft.
- The results support encouraging developers to optimize EC and HMOS-based sensors for acceptable performance under flight conditions, so that their compact configurations can be utilized.

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Appendix A

Sensor Survey

Tables A1-A5

Appendix A1
Table A1. Sensors for Ozone

Principle	Manufacturer / Supplier	Instrument(s)	References	Notes
COTS				
Color	ChromAir	ChromAir Ozone Badge	A1.1	No electronic readout
Color	Ozone Solutions	B-1D Ozone Discovery Badge	A1.1-3	bleaching indigo blue; single use passive sampler
EC	Draeger	DraegerSensor O_3 for Draeger monitors	A1.4,5	30 mm dia × 70 mm; LOD = 14 ppb; max 5 ppm, half cell reactions given; LOD = 10 ppb
EC	Eco Sensors via KWJ Engineering	Pocket Ozone for Air	A1.6	nanocell micropower; 0-5 ppm, US patent 5744697
EC	Environmental Sensors Company	Z-1200	A1.7	LOD = 10 ppb; atm P ±10%; RH 15-90%; NO_2 interference
EC	Ozone Solutions	OMC-1108	A1.8,9	low concentration unit used in LBNL study
EC	YES Environment Technologies	YESair	A1.10	
Lumin	Gesellschaft fur Angewandte Systemtechnik	OS-B-2 ozonesonde	A1.11	chemiluminescence from O_3 reaction with organic dye; refs to Schurath 1991, Gusten 1992; lifetime 2000 ppb-hr
Lumin	JSC Optec Ltd	3.02 P-A 1,2	A1.12,13	chemiluminescence from O_3 reaction with proprietary solid-phase reactant
MOS	Aeroqual	Ozone Monitors Series 300&500; Remote sensor head option for series 300& 500	A1.14-18	S500L (low range) in LBNL study

Principle	Manufacturer / Supplier	Instrument(s)	References	Notes
MOS	Eco Sensors via KWJ Engineering	Model C-30ZX, Ecozone Model EZ-1X	A1.19-20	0-0.14 ppm; same sensor as Aeroqual HMOS (per Joel of Ozone Solutions 24 April 2007); LOD = 20 ppb; 15-27 °C.
MOS	Microchemical Systems	MiCS-2610	A1.21-25	common interferents (VOCs, H_2O, ethanol, increasing T) act like reducing gases so resistance decreases and apparent ozone signal decreases
PS	Ogawa and Company	Ogawa passive sampler	A1.26	coated honeycomb
UV	2B Tech	2BTech Model 202	A1.26-29	UV absorption, used in present study
UV	Teledyne Advanced Pollution Instrumentation	API Model 400	A1.30-31	UV absorption, used in present study; reference instrument
UV	three	2BTech, TEI-49, TEI 49C, Dasibi 1003-AH	A1.31	correcting response to RH
Var	Ozone Solutions	various	A1.32	
Emerging				
EC	Synkera Technologies Inc.	Prototype	A1.34-36	nanostructured, anodic alumina nanotemplates, monodisperse nanoporous ceramic membranes, ceramic microcomponents LOD = 12 ppb; solid polymer electrolyte; nano-dot electrodes; nanoscale anodic aluminum oxide
Research				
Color	Texas Tech University	Prototype	A1.37	bleaching of indigotrisulfonate by O_3; LOD = 1 ppb; compensation for evaporation of indigotrisulfonate

Principle	Manufacturer / Supplier	Instrument(s)	References	Notes
Lumin	Universitat Karlsruhe	Prototype	A1.38	chemiluminescence from O_3 reaction with organic dye on silica gel; for atmospheric research
MOS	Australian universities	Prototype	A1.39	SAW on InO_x and SiN_x MOS sensors
MOS	Crete universities	Prototype	A1.40	conductivity change in ZnO nanostructures on glass; ZnO response more specific than SnO_2
MOS	British universities	Prototype	A1.41	WO_3 semi-conductor, drift correction
MOS	French university	Prototype	A1.42	tailoring conductivity in pseudo-Schottky structures to overcome selectivity problems and high temperature requirements of electrochemical and MOS sensors
MOS	German university	Prototype	A1.24	improved MOS selectivity by temperature cycling; low power, high sensitivity but limited selectivity and stability over operational lifetime; sensors from Microchemical Systems; see *micsdatasheet.pdf*
MOS	Moldova university	Prototype	A1.43	SnO_2 thin film responds faster than thick
MOS	Moldova university	Research	A1.44	RH-dependent response
MOS	SILSENS Company	Microsens semiconductor gas sensor MGS 3003	A1.45	SnO_2; explanation of instability in resistance change of MOS in response to ozone: conductivity change at high T
MOS	Spanish & French universities	Prototype	A1.46	increase in resistance WO_3 semi-conductor; MEMS array; smaller grain size-inc reproducibility
MOS	UK universities	Prototype	A1.47	WO_3 two temperature operating mode; sensitivity change with use
Poly	Australian universities	Prototype	A1.48	polymer-coated filament

References - Appendix A1
Table A1. Sensors for Ozone

Ref	pdf	Reference
COTS		
A1.1	ChromAir vs Ozone Discovery.pdf	*http://www.ozonesupplies.com/files/ChromAirVsOzoneDiscovery.pdf*
A1.2	Ozone Discovery Badge.pdf	*http://www.ozonemeters.com/ozone-pdf/B1-D.pdf*
A1.3	ntttechnical-ozone passive sampling-2006.pdf	*http://www.ntt-review.jp/archive/ntttechnical.php?contents=ntr200608006.pdf*
A1.4	DraegerSensor_O3_9023659_03_2006_de_en_es_fr.pdf	*http://www.draeger.com/ST/internet/pdf/Master/En/gt/Sensors/9023659_03_2006_de_en_es_fr.pdf*
A1.5	DraegerSensor_O3_9023660_03_2006_d_e.pdf	*http://www.draeger.com/9023660_03_2006_d_e.pdf*
A1.6	KWJ Engineering Pocket Ozone for Air.pdf	*http:/www.kwjengineering.com/products/ozone/portable-instruments-for-ozone/pocket-ozone-for-air*
A1.7	Ozone monitor-Z-1200 2009-12-06.pdf	*http://www.environmentalsensors.com/PDF/ESC New Brochure/ozone z-1200.pdf*
A1.8	OMC-1108 Manual.pdf	*http://www.ozonesolutions.com/manual/OMC-1108_Rental_manual.pdf*
A1.9	Ambler_O3 sensor low P_IAC-08-C2.I.17.pdf	N. P. Ambler, R. Fevig and N. Patel, Solid-state sensor behavior in reduced-pressure environments demonstration using an experimental indium tin oxide gas sensor for ozone sounding, IAC-08-C2.I.17, Proceedings of the 59th International Astronautical Conference, Sept 29-Oct 2, 2008, Glasgow, Scotland
A1.10	YESairManual.pdf	*http://www.yestek.com/PDF/YESairManual.pdf*
A1.11	McKendry-JAtm&OceanicTech-O3.pdf	I. G. McKendry, D. G. Steyn, S. O'Kane, P. Zawar-Reza and D. Heuff, Lower Tropospheric ozone measurements by light aircraft equipped with chemiluminescent sonde, *J. Atmos. And Oceanic Technol.*, **15**, 136-143 (1998)
A1.12	Ozone_Optec _Battelle_EVS_Optec2008.pdf	*http://www.battelle.org/ASSETS/F666CA6140524DF2A1E6CD4601CB4DFF/VS_Optec Feb 2008.pdf*

Ref	pdf	Reference
A1.13	Ozone_Optec_ETV_Battelle.pdf	*http://www.nationalsecurity.battelle.org/ASSETS/9CC9F78B854B433DAC4C3D639A05C3BC/ETV JSC Optec Feb 2008 (2).pdf*
A1.14	Aeroqual User Guide Series 300 & 500 Monitors.pdf	*http://www.aeroqual.com/products/downloads/AQL-S300-S305-S500-S505-User-Guide.pdf*
A1.15	AQL_S300_Specs.pdf	*http://www.aeroqual.com/_dev/products/downloads/AQL_S300_Specs.pdf*
A1.16	Aeroqual_gas sensitive semi-conductor-iet200605_i.pdf	*http://www.aeroqual.com/about/our-technology.php*
A1.17	Aeroqual_Sensor Specifications.pdf	*http://www.aeroqual.com//gases/gas-sensor-heads.php*
A1.18	AQL_R10_Specs.pdf	*http://www.olgear.com/sites/18/images/AQL_R10_Specs.pdf*
A1.19	EcoSensor-C-30ZX.pdf	*http://www.ecosensors.com/c30zx.pdf*
A1.20	EcoSensor-ez1x.pdf	*http://www.ecosensors.com/ez1x.pdf*
A1.21	MiCS-ozone_a1a-mics_an1_1_v11.pdf	*http://www.e2v.com/assets/media/files/sensors_datasheets/Metal_Oxide/mics_an1.pdf*
A1.22	micsdatasheet.pdf	*http://www.virtintern.duke.edu/2003fall/ozone/micsdatasheet.pdf*
A1.23	O3-cell-phonesnapshot.ppt	*http://www.virtintern.duke.edu/2003fall/ozone/snapshot.ppt*
A1.24	Losch-O3-2008.pdf	M. Lösch , M. Baumbach and A. Schütze, Ozone detection in the ppb-range with improved stability and reduced cross sensitivity, Sensors and Actuators B, **130**, 367–373 (2008)
A1.25	Sensors - Articles.pdf (overview of microfabricated MOS sensors)	http://www.archives.sensorsmag.com/articles/0999/109/main.shtml
A1.26	Final Report-1262-RP-Batelle.pdf	C.W. Spicer, M.J. Murphy, M.W. Holdren, J.D. Myers, I.C. MacGregor, C. Holloman, R.R. James, K.Tucker and R. Zaborski, Relate Air Quality and Other Factors to Comfort and Health Symptoms Reported by Passengers and Crew on Commercial Transport Aircraft (Part I) (ASHRAE Project 1262-TRP), Final Report to American Society for Heating, Refrigerating and Air Conditioning Engineers, 337 pp. (2004)
A1.27	birks_ACER_sensor_wkshp_2005.pdf `	J. Birks and M. Bollinger, Portable ozone, NO and CO instruments for monitoring cabin air of commercial airliners, presented at the FAA Center of Excellence ACER Workshop, Jan 20, 2004; posted at *http://acer.eng.auburn.edu/sensor_pres/birks.pdf*

Ref	pdf	Reference
A1.28	Bognar&Birks-1996 AnChem O3-ac9604189.pdf	J.A. Bognar and J.W. Birks, Miniaturized ultraviolet ozonesonde for atmospheric measurements, *Anal. Chem.*, **68**, 3059-3062 (1996)
A1.29	Wilson&BirksES&T 2006-H2O interf O3-es052590.pdf	K.L. Wilson and J.W. Birks, Mechanism and elimination of a water vapor interference in the measurement of ozone by UV absorbance, *Environ. Sci. Technol.*, **40**, 6361-6367 (2006)
A1.30	Teledyne-API-O3_400e.pdf	*http://www.teledyne-api.com/pdfs/400e.pdf*
A1.31	reference-equivalent-methods-list.pdf	*http://www.epa.gov/ttnamti1/files/ambient/criteria/reference-equivalent-methods-list.pdf*
A1.32	Ozone solutions_mini-catalog.pdf	*http://www.ozonesupplies.com/custom_catalog/downloads/1260404411/mini_catalog.pdf*
Emerging		
A1.33	Sensors - Nanostructured Electrochemical ozone sensor.pdf	*http://www.sensorsmag.com/sensors-mag/news/nanostructured-electrochemical-ozone-monitors-6048*
A1.34	Synkera_Tech ProfileEChem Sensors_2006.pdf	*http://www.synkera.com/pdf/Tech Profile EChem Sensors 08-2006.pdf*
A1.35	Synkera_EChem_pressrelease_112608.pdf	*http://www.synkera.com/pdf/ECO3 press release_112608.pdf*
A1.36	Synkera Nano-microfab tech.pdf	*http://www.synkera.com/Products/membranes_and_mems.html*
A1.37	Li-O3_porous_tube_colorimeter.pdf	J. Li, Q. Li, J.V. Dyke, P.K. Dasgupta, Atmospheric ozone measurement with an inexpensive and fully automated porous tube collector-colorimeter, *Talanta*, **74**, 958-964 (2008)
A1.38	Gusten-O3-2002.pdf	H. Güsten, G. Heinrich, E. Monich, M. Nolle and J. Weppner' Two Automated Ozone Analyzers for Use on Civil Aircraft Operating in the Tropopause Region, *J. Atmos. Oceanic Technol.*, **20**, 292-300 (2002)
A1.39	Fechete-SAW-O3-2006.pdf	A.C. Fechete, W. Wlodarski, K. Kalantar-Zadeh, A.S. Holland, J. Antoszewski, S. Kaciuli, L. Pandolfi, SAW-based gas sensors with rf sputtered InO_x and PECVD SiN_x films: Response to H_2 and O_3 gases, *Sensors and Actuators B*, **118**, 362-367 (2006)

Ref	pdf	Reference
Research		
A1.40	Kenanakis-O3-2007.pdf	G. Kenanakis, D. Vernardou, E. Koudoumas, G. Kiriakidis, N. Katsarakis, Ozone sensing properties of ZnO nanostructures grown by the aqueous chemical growth technique, *Sensor and Actuators B,* **124,** 187-191 (2007)
A1.41	Aliwell-O3-2001.pdf	S.R. Aliwell, J.F. Halsall, K.F.E. Pratt, J. O'Sullivan, R.L. Jones, R A Cox, S.R. Utembe, G.M. Hansford and D.E., Williams, Ozone sensors based onWO_3: a model for sensor drift and a measurement correction method, *Meas. Sci. Technol.* **12**, 684-690 (2001)
A1.42	Mazet-O3-2007.pdf	L. Mazet, C. Varenne, J. Brunet, K. Wierzbowska, A. Pauly, An original methodology dedicated to real-time detection of oxidizing gases based on pseudo-Schottky diode junction, *Sensors and Actuators B,* **122**, 535-541 (2007)
A1.43	Korotchenkov-O3-2007.pdf	G. Korotcenkov, I. Blinov, M. Ivanov and J.R. Stetter, Ozone sensors on the base of SnO2 films deposited by spray pyrolysis, *Sensors and Actuators B*, **120,** 679-686 (2007)
A1.44	Korotchenkov-O3-RH-2007.pdf	G. Korotcenkov, I. Blinov, V. Brinzari and J.R. Stetter, Effect of air humidity on gas response of SnO2 thin film ozone sensors, *Sensors and Actuators B*, **122**, 519-526 (2007)
A1.45	Berry-O3-2008.pdf	L. Berry and J. Brunet, Oxygen influence on the interaction mechanisms of ozone on SnO2 sensors (Review), *Sensors and Actuators B*, **129**, 450-458 (2008)
A1.46	Vallejos-O3-2007.pdf	S. Vallejos, V. Khatko, K. Aguir, K.A. Ngo, J. Calderer, I. Gràcia, C. Cané, E. Llobet and X. Correig, *Sensors and Actuators B*, **126**, 573-578 (2007)
A1.47	Utembe-O3-2006.pdf	S.R. Utembe,, G.M. Hansford, M.G. Sanderson, R.A. Freshwater, K.F.E. Pratt, D.E. Williams, R.A. Cox and R.L. Jones, An ozone monitoring instrument based on the tungsten trioxide (WO3) semiconductor, *Sensors and Actuators B,* **114**, 507-512 (2006)
A1.48	Jin-O3-2004.pdf	G. Jin, J. Norrish, C. Too and G. Wallace, Polypyrrole filament sensors for gases and vapours, *Cur. Appl. Phys.*, **4**, 366-369 (2004)

Appendix A2
Table A2. Illustrative Sensors for Pressure

Principle	Manufacturer / Supplier	Instrument	References	Notes
COTS				
Unknown	TSI	Q-Trak 7565, Q-Trak 7565, IAQ instruments list	A2.1-3	
Var	various	various	A2.4	review, mature technology
Piezo	Vaisala	PTB 100	A2.5	piezoresistive

References Appendix A2
Table A2. Illustrative Sensors for Pressure

Ref	pdf	Reference
COTS		
A2.1	IAQDOM2980236RevBWebSecure.pdf	*http://www.ecoenvironmental.com.au/eco/downloads/dust_General_Indoor_Air_Quality_Measurements.pdf*
A2.2	TSI-7565_Q-trak_298057D_USA.pdf	*http://www.tsi.com/uploadedFiles/Product_Information/Literature/Spec_Sheets/7565_Q-Trak_2980572D_USA.pdf*
A2.3	TSI-Indoor-Air-Quality-Handbook-2009.pdf	*http://www.ecoenvironmental.com.au/eco/downloads/dust_General_Indoor_Air_Quality_Measurements.pdf*
A2.4	Fundamentals of Pressure Sensors_Sensor Mag.pdf	*http://www.sensorsmag.com/sensors/pressure/fundamentals-pressure-sensor-technology-846*
A2.5	Final Report-1262-RP-Batelle.pdf	C.W. Spicer, M.J. Murphy, M.W. Holdren, J.D. Myers, I.C. MacGregor, C. Holloman, R.R. James, K.Tucker and R. Zaborski, Relate Air Quality and Other Factors to Comfort and Health Symptoms Reported by Passengers and Crew on Commercial Transport Aircraft (Part I) (ASHRAE Project 1262-TRP), Final Report to American Society for Heating, Refrigerating and Air Conditioning Engineers, 337 pp. (2004)

Appendix A3
Table A3. Sensors for Carbon Monoxide

Principle	Manufacturer / Supplier	Instrument	References	Notes
COTS				
EC	Airtest	TR2000	A3.1,2	less T and RH interference than MOS/solid state sensors
EC	City Technology Ltd	9CF CiTiceL	A3.3	used in Langan DataBear CO monitors
EC	Draeger	DraegerSensor_XS_EC CO, DraegerSensor XS R CO for Pac III, MiniWarn, DraegerSensor XXS CO, for Draeger Pac 5000 personal monitor; PAC 7000	A3.4-8	30 mm dia × 70 mm; 0-100, 0-500, 0-2000 ppm, Pac III used in ASHRAE Part I sensor study, miniaturized 0-2000 ppm
EC	Langan Products, Inc.	DataBear CO Measurers, DataBear T15n	A3.9-11	used in present lab study
EC	Quest Technologies	AQ 5000 Pro, AQ 5001 Pro; SafeCheck, SafeTest, SafeLog; EVM-4, EVM-7	A3.12-14	0-500 ppm, 01-1000 ppm
EC	Testo	Model 350 Portable Multigas emission analyzer	A3.15	designed for testing emission from engines
EC	Transducer Technology	Pocket CO, Pocket CO 300, CO-MFS	A3.16-19	nanotech-enabled; range 0-600 ppm CO; other products to 1500 ppm
EC	TSI	Q-Trak 8554-Plus with CO, Q-Trak 7565	A3.20-21	0-500 ppm
EC	YES Environment Technologies	YES-2005-4 optional sensor, YESair, YESplus	A3.22-26	0-50 ppm
IR	Thermo Scientific	TECO Model 48C	A3.27	IR absorption at 4.6 microns; reference instrument for LBNL
IR	Edinburgh Instruments	Gascard NG, Gascard I	A3.28-29	CO LOD = 100 ppm

Principle	Manufacturer / Supplier	Instrument	References	Notes
PAS	Applied Nanotech	Photacoustic sensor platform	A3.30	solid state light source
MOS	Aeroqual	Series 500	A3.31-32	used in present chamber study
MOS	Airtest	TR1000	A3.33	RH dependent response
MOS	Applied Nanotech	gated MOS platform	A3.34-35	Microfabricated metal oxide sensor
MOS	Figaro	TGS 2442	A3.36-37	SnO_2
Emerging				
EC	Transducer Technology via KWJ Eng	T-series Carbon Monoxide	A3.38	nanotech-enabled
MOS	Applied Sensor Gmbh, er al.	prototype	A3.39	MEMS-MOS conductivity change; PtO_2, SnO_2, PdO_2: microarrays
Research				
CNT	Clemson University & UC Davis	single walled carbon nanotube nanosensor	A3.40	change in dielectric constant by single walled carbon nanotubes
CNT	Penn State Univ	research	A3.41	resistance change of MWCNT
CNT	Smiths licensed from Caltech & NASA/JPL	primarily chemiresitor chemical sensing; also NDIR and electrochemical	A3.42	disposable chemiresistors to detect fluid leaks-military application
CNT		(theoretical study)	A3.43	deformed carbon nanotubes
Cond	Georgia Inst Technology	research	A3.44	coated porous Si; goal: microfabricated arrays
IR	Rice University	prototype	A3.45	865 nm

Principle	Manufacturer / Supplier	Instrument	References	Notes
MOS	Figaro	SnO_2; Taguchi-type sensors (TGS812, hydrocarbons & 824, CO)	A3.46	Taguchi structure ceramic tubes
VUV	NOAA, Japanese research organizations	prototype; vacuum ultraviolet fluorescence	A3.47	Holloway (NOAA) design modified to exclude H_2O interference by use of crystalline quartz window (Holloway et al. Comparison of vacuum ultraviolet fluorescence and tunable diode laser absorption measurements)

References - Appendix A3
Table A3. Sensors for Carbon Monoxide

Ref	pdf	Reference
COTS		
A3.1	Airtest CO TR2000-manual-2009.pdf	*https://www.airtest.com/support/manual/TR2000man.pdf*
A3.2	AirTest CO TR2000-2009.pdf	*https://www.airtest.com/support/datasheet/TR2000.pdf*
A3.3	CiTiceL_9CF.pdf	*www.citytech.co.uk/PDF-Datasheets/9cf.pdf*
A3.4	DraegerSensor_XS_R_CO_9023604_xsr_d_e.pdf	*http://www.draeger.com/ST/internet/pdf/Master/En/gt/9023604_xsr_co_d_e.pdf*
A3.5	DraegerSensor XS EC_CO_9023361_xs_co_d_e.pdf	*http://www.draeger.com/ST/internet/pdf/Master/En/gt/9023361_xs_co_d_e.pdf*
A3.6	Final Report-1262-RP-Batelle.pdf	C.W. Spicer, M.J. Murphy, M.W. Holdren, J.D. Myers, I.C. MacGregor, C. Holloman, R.R. James, K.Tucker and R. Zaborski, Relate Air Quality and Other Factors to Comfort and Health Symptoms Reported by Passengers and Crew on Commercial Transport Aircraft (Part I) (ASHRAE Project 1262-TRP), Final Report to American Society for Heating, Refrigerating and Air Conditioning Engineers, 337 pp. (2004)
A3.7	draegersensor_xxs_co_ds_9023816_de_en_fr_nl.pdf	*http://www.draeger.us/media/10/02/45/10024575/draegersensor_xxs_co_ds_9023816_de_en_fr_nl.pdf*
A3.8	pac5000_br_90xxxxx_en.pdf	*http://www.draeger.com/media/10/03/23/10032307/single_gas_detection_br_9046540_en.pdf*
A3.9	Langan CO Measurer Overview.pdf	*http://www.langan.biz/Site/CO Measurer.html*
A3.10	Langan DataBear T15n Specifications.pdf	*http://www.langan.biz/Site/T15n Specifications.html*
A3.11	Langan DataBear CO BF111_keyspan.pdf	*http://www.langan.biz/pdf_web_files/BF111_keyspan.pdf*
A3.12	Quest-IAQ-2009.pdf	*http://www.questtechnologies.com/ProductCategory/IAQ-and-Particulate-Monitors_13.aspx*

Ref	pdf	Reference
A3.13	SafeTest gas sensors-098-473-2009.pdf	*http://www.questtechnologies.com/QuestFiles/90/098-473.pdf.pdf (sic)*
A3.14	Quest-IAQ PM CO EVM series 2009.pdf	*http://www.questtechnologies.com/Assets/Documents/EVM%20Brochure_updated1_10.pdf*
A3.15	CO-CO2_Battelle-test_01_vr_testo_350.pdf	J. Myers, T. Kelly, Z. Willenberg, Karen Riggs, Environmental Technology Verification Report, Testo Inc. Model 350 Portable Multigas Emission Analyzer, Batelle, Columbus, Ohio (2003)
A3.16	pocketcospec.pdf	Updated documentation at *http://www.kwjengineering.com/wp-content/uploads/2008/06/pocket-co-model-300-datasheet-r16.pdf*
A3.17	stetter_sensor_wkshp_2005.pdf	J.R. Stetter, Nanotechnology and advanced sensors for IAQ, presented at the ACER workshop on sensors, Jan. 2005; available at *http://acer.eng.auburn.edu/sensor_pres/stetter.pdf*
A3.18	pocket-co-model-300-datasheet.pdf	*http://www.kwjengineering.com/wp-content/uploads/2008/06/pocket-co-model-300-datasheet-r16.pdf*
A3.19	Transducer Tech sensor-rco1000lrh-rco1000lrhf.pdf	*http://www.kwjengineering.com/wp-content/uploads/2008/05/rco1000lrh-rco1000lrhf.pdf*
A3.20	qtrak.pdf	(2005 version of spec sheet-see qtrak 7565 …pdf)
A3.21	TSI-7565_Q-Trak_2980572D_USA.pdf	*http://www.tsi.com/uploadedFiles/Product_Information/Literature/Spec_Sheets/7565_Q-Trak_2980572D_USA.pdf*
A3.22	yes205literature.pdf	*http://www.yestek.com/PDF/yes205literature.pdf*
A3.23	YES205-Manual.pdf	*http://www.yestek.com/PDF/YES205-Manual.pdf*
A3.24	YESair_literature.pdf	*http://www.yestek.com/PDF/YESair_literature.pdf*
A3.25	YESair-manual-2009.pdf	*http://www.yestek.com/PDF/YESairManual.pdf*
A3.26	YESplus_literature.pdf	*http://www.yestek.com/PDF/YESplus_literature.pdf*
A3.27	TECO Model 48C_productPDF_12767.pdf, current model is 48i	*http://www.thermo.com/eThermo/CMA/PDFs/Product/productPDF_12767.pdf*
A3.28	Gascard NG Datasheet Rev1.pdf	*http://www.edinst.com/pdf/Gascard NG Datasheet Rev1.pdf*

Ref	pdf	Reference
A3.29	Gascard II Plus.pdf	*http://www.edinst.com/pdf/Gascard_II_Plus_Oct08.pdf*
A3.31	Aeroqual GSS Technology.pdf	*http://www.aeroqual.com/about/our-technology.php*
A3.32	Aeroqual_GSS_Technology_Background.pdf	See *http://www.aeroqual.com/about/our-technology.php*
A3.33	AirTest CO TR1000 2009.pdf	*https://www.airtest.com/support/datasheet/TR1000.pdf*
A3.36	Figaro-RuOxide-CO-2442.pdf	*http://www.figarosensor.com/products/2442pdf.pdf (sic)*
A3.37	Figaro MOS characteristics.pdf	*http://www.figarosensor.com/products/common(1104).pdf*
Emerging		
A3.30	Applied Nanotech Sono Photonic Sensors.pdf	*http://www.appliednanotech.net/tech/sps.php*
A3.34	GMOS Carbon Monoxide Sensor.pdf	*http://www.sensorsportal.com/HTML/DIGEST/may_06/Carbon_Monixide_Sensor.htm*
A3.35	GMOS-CO-ANI-2006-02-15.pdf	*http://www.appliednanotech.net/news/060215_co_sensor.php*
A3.38	KWJ Engineering Tseries MEMS nanopart CO sensor.pdf	*http://www.kwjengineering.com/news/archives/147*
A3.39	Blaschke-2006.pdf	M. Blaschke, T. Tille, P. Robertson, S. Mair, U. Weimar, and H. Ulmer, MEMS Gas-Sensor Array for Monitoring the perceived Car-Cabin Air Quality, *IEEE Sensors Journal*, **6**, 1298-1308 (2006)
A3.40	Chopra-CO-CNT-2003.pdf	S. Chopra, K. McGuire, N. Gothard, and A. M. Raoa, A. Pham, Selective gas detection using a carbon nanotube sensor, *App. Phy. Letters*, **83**, 2280-2282 (2003)

Ref	pdf	Reference
Research		
A3.41	Varghese 2001-CO.pdf	O.K. Varghese, P.D. Kichambre, D. Gong, K.G. Ong, E.C. Dickey, C.A. Grimes, Gas sensing characteristics of multi-wall carbon nanotubes, *Sensors and Actuators B,* **81**, 32-41 (2001)
A3.42	sunshine_ACER-sensor_wkshp_2005.pdf	S. Sunshine, Distributed sensing for cabin air quality, presented at the FAA Center of Excellence ACERWorkshop, Jan 20, 2004. *http://acer.eng.auburn.edu/sensor_pres/sunshine.pdf*
A3.43	CO-CNT-2004-nl034873d.pdf	L. B. da Silva, S. B. Fagan, and R. Mota, Ab initio study of deformed carbon nanotube sensors for carbon monoxide molecules, *Nano Letters*, **4**, 65-67 (2004)
A3.44	Lewis 2005.pdf	S. E. Lewis, J.R. DeBoer, J.L. Gole, P. J. Hesketh, Sensitive, selective, and analytical improvements to a porous silicon gas sensor, *Sensors and Actuators B*, **110**, 54-65 (2005)
A3.45	Topfer_1997.pdf	T. Topfer, K.P. Petrov, Y. Mine, D. Jundt, R.F. Curl and F.K. Tittel, Room-temperature mid-infrared laser sensor for trace gas detection, *Applied Optics*, **36**, 8042-8049 (1997)
A3.46	Alexander_1996.pdf	P.W. Alexander, L.T. Di Benedetto, T. Dimitrakopoulos, D. B. Hibbert, J.C. Ngila, M.Sequeira, D. Shiels. Field-portable flow-injection analysers for monitoring of air and water pollution, *Talanta*, **43**, 915-925 (1996)
A3.47	vuv flouresce fast CO.pdf	N. Takegawa, K. Kita, Y . Kondo, Y. Matsumi, D.D. Parrish, J.S. .Holloway, M. Koike, Y. Miyazaki, N. Toriyama, S. Kawakami, and T. Ogawa, Airborne vacuum ultraviolet resonance fluorescence instrument for in situ measurement of CO, *J. Geophys. Res.*, **106,** 24,237-24,244 (2001)

Appendix A4
Table A4. Sensors for Carbon Dioxide

Principle	Manufacturer / Supplier	Instrument	References	Notes
COTS				
EC	Figaro	TGS4160	A4.1	solid electrolyte
IR	AirTest	AirTest CO_2 300-8000 ppm, TR9503, Rainbow CO_2 Engine, TR9290, EE80	A4.2-7	300-8000 ppm; 8.3 inch pathlength for 300 ppm LOD
IR	Draeger	Polytron IR CO_2	A4.8	
IR	Edinburgh Instruments	Gascard NG, Gascard II, MyCO_2, GasCheck for CO_2, guardcard for CO_2, IRgaskiT, AirCheck P65	A4.9-15	
IR	GE Industrial Sensing	Telaire 7000 Series	A4.16-17	dual beam
IR	LICOR	LI-7000 CO_2/H_2O Analyzer	A4.18	reference instrument in present study
IR	PP Systems	EGM-4, SBA-4	A4.19-20	optional RH sensor available, OEM with optional RH sensor available
IR	Quest Technologies	EVM-4, EVM-7	A4.21-22	multi-parameter
IR	TSI	Q-Trak 8554, Q-Trak 8554-Plus with CO; Q-Trak 7565	A4.23-26	
IR	Vaisala	GMP343, GMW21	A4.27	single lamp dual wavelength
IR	YES Environment Technologies	YESair, YES-205, YESplus, YES Falcon II	A4.28-34	
PAS	LumaSense Technologies	1314 Multi-gas Monitor	A4.35	photoacoustic IR

Principle	Manufacturer / Supplier	Instrument	References	Notes
Emerging				
IR	Icx Photonics	Sensor chip^{tm} CO_2 Sensor, SensorChip 4P	A4.36-37	MEMS; 0-100%, chip by IMT, chip area = $1in^2$
PAS	Applied Nanotech	Photacoustic Sensor Platform	A4.38	solid state light source
Research				
CNT	Nanomix, Inc	Nanoelectronic carbon dioxide detection device	A4.39	*Sensation*^{tm} technology
CNT	Penn State Univ	research	A4.40	change in resonant frequency in multi-walled carbon nanotube-SiO_2 composite; ref to uncoated, SiO_2, coated and MWCNT sensor for T and RH compensation
CNT	Penn State Univ	research	A4.41	resistance change of MWCNT
Cond	Japanese universities	research	A4.42	resistance change; to operate at high RH
EC	Japanese universities	$Na_3Zr_2Si_2PO_{12}$ on metal oxide electrode	A4.43	to control RH-dependence of electrochemical detection of CO_2 at room temperature

References - Appendix A4
Table A4. Sensors for Carbon Dioxide

Ref	pdf	Reference
COTS		
A4.1	Figaro-CO2-EC_4160.pdf	*http://www.figarosensor.com/products/4160pdf.pdf.*
A4.2	lengthmatters.pdf	*https://www.airtest.com/support/reference/lengthmatters.pdf*
A4.3	AirTest 9503 CO2 2009.pdf	*https://www.airtest.com/support/datasheet/TR9503.pdf*
A4.4	Iowa Energy Center-CO2 product sensor testing.pdf	Iowa Energy Center, Product Testing Report-Wall Mounted Carbon Dioxide (CO_2) Transmitters, (G. Maxwell, principal investigator) 49 pp. 2009
A4.5	TR9290.pdf	*https://www.airtest.com/support/datasheet/TR9290.pdf*
A4.6	AirTest-EE80-dual beam NDIR.pdf	https://www.airtest.com/support/datasheet/EE80.pdf
A4.7	airtest-k30overview.pdf	*https://www.airtest.com/support/datasheet/k30overview.pdf*
A4.8	Final Report-1262-RP-Batelle.pdf	C.W. Spicer, M.J. Murphy, M.W. Holdren, J.D. Myers, I.C. MacGregor, C. Holloman, R.R. James, K.Tucker and R. Zaborski, Relate Air Quality and Other Factors to Comfort and Health Symptoms Reported by Passengers and Crew on Commercial Transport Aircraft (Part I) (ASHRAE Project 1262-TRP), Final Report to American Society for Heating, Refrigerating and Air Conditioning Engineers, 337 pp. (2004)
A4.9	Gascard NG Datasheet Rev1.pdf	*http://www.edinst.com/pdf/Gascard%20NG%20Datasheet%20Rev1.pdf*
A4.10	Gascard II Plus.pdf	*http://www.edinst.com/pdf/Gascard%20II%20Plus.pdf*
A4.11	myco2_b.pdf	*http://www.edinst.com/pdf/myco2_b.pdf*
A4.12	GasCheck.pdf	*http://www.edinst.com/pdf/GASCHECK%20NEW%2029%201%2009.pdf*
A4.13	Guardcard.pdf	*http://www.edinst.com/pdf/Guardcard.pdf*
A4.14	irgaskit.pdf	*http://www.edinst.com/pdf/irgaskit.pdf*
A4.15	AirCheckIP65.pdf	*http://www.edinst.com/pdf/AirCheckIP65.pdf*
A4.16	Telaire_7001manual.pdf	*http://www.gesensing.com/downloads/manuals/7001manual.pdf*

Ref	pdf	Reference
A4.17	Telaire_CO2_IR_920_315a.pdf	*http://www.edinst.com/pdf/telaire/telaire%207001.pdf*
A4.18	LI7000.pdf	*http://www.licor.com/env/PDF/LI7000.pdf*
A4.19	EDSEGM4.pdf	http://www.ppsystems.com/Literature/EDSEGM4.pdf
A4.20	EDSSBA4.pdf	*http://www.ppsystems.com/Literature/EDSSBA4.pdf*
A4.21	Quest-IAQ PM CO EVM series 2009.pdf	*http://www.questtechnologies.com/Assets/Documents/EVM%20Brochure.pdf*
A4.22	Quest-IAQ-2009.pdf	*http://questtechnologies.com/QuestFiles/61/QuestIAQ.pdf*
A4.23	qtrak.pdf	*http://www.tsi.com/uploadedFiles/Product_Information/Literature/Spec_Sheets/qtrak.pdf*
A4.24	TSI-Indoor-Air-Quality-Handbook-2009.pdf	*http://www.ecoenvironmental.com.au/eco/downloads/dust_General_Indoor_Air_Quality_Measurements.pdf*
A4.25	TSI-7515-25-35-45-IAQ-Calc.pdf	*http://www.tsi.com/uploadedFiles/Product_Information/Literature/Spec_Sheets/2980573-7515-25-35-45-IAQ-Calc.pdf*
A4.26	TSI-7565_Q-trak_298057D_USA	*http://www.tsi.com/uploadedFiles/Product_Information/Literature/Spec_Sheets/7565_Q-Trak_2980572D_USA.pdf*
A4.27	Vaisala GMP343_datasheet.pdf	*http://www.vaisala.com/files/GMP343_Datasheet.pdf*
A4.28	YESair_literature-2009.pdf	*http://www.yestek.com/PDF/YESair_literature.pdf*
A4.29	YESair-manual-2009.pdf	*http://www.yestek.com/PDF/YESairManual.pdf*
A4.30	yes205literature.pdf	*http://www.yestek.com/PDF/yes205literature.pdf*
A4.31	YES205-Manual.pdf	*http://www.yestek.com/PDF/YES205-MANUAL.PDF*
A4.32	YESplus_literature.pdf	*http://www.yestek.com/PDF/YESplus_literature.pdf*
A4.33	Falcon-II-manual-Rev-B-2009.pdf	*http://www.yestek.com/images/pdf/Falcon-II%20Rev-B%20Sept-1-09%20single-page.pdf*
A4.34	YES Falcon2_lit1-2009.pdf	*http://www.yestek.com/images/pdf/Falcon2_lit1.pdf*
A4.35	LumaSense_PD_1314.pdf	*http://www.bruel.sk/PDF_files/PD_1314.pdf*

Ref	pdf	Reference
Emerging		
A4.36	SensorChipCO2-ds.pdf	*http://photonics.icxt.com/uploads/files/Datasheets/SensorChipCO2-ds.pdf*
A4.37	Mems_CO2_sensor.pdf	*http://www.osti.gov/bridge/servlets/purl/860161-UpDeA3/860161.pdf*
A4.38	Applied Nanotech-photoacoustic sensors.pdf	*http://www.appliednanotech.net/tech/sps.php*
Research		
A4.39	Star-AdvMat 2004_Nanomix_Nanoelectronic_Carbon_Sensors.pdf	A. Star, T.-R. Han, V. Joshi, J.-C. Gabriel and Grüner, Nanoelectronic carbon dioxide sensors, *Adv. Mater.* **16**, 2049-2052 (2004)
A4.40	Ong-2002.pdf	K.G. Ong, K. Zeng, and C. A. Grimes A wireless, passive carbon nanotube-based gas sensor, *IEEE Sensors J.* **2** (2), 82-88 (2002)
A4.41	Varghese 2001-CO.pdf	O.K. Varghese, P.D. Kichambre, D. Gong, K.G. Ong, E.C. Dickey, C.A. Grimes, Gas sensing characteristics of multi-wall carbon nanotubes, *Sensors and Actuators B,* **81**, 32-41 (2001)
A4.42	Oho-CO2-2002.pdf	T. Oho, T. Tonosaki, K. Isomura, K. Ogura, A CO2 sensor operating under high humidity, *J. Electroanalytical Chem.*, **522,** 173–178 2002)
A4.43	Obata-CO2-2005.pdf	K. Obata, S. Kumazawa, S.Matsushima, K. Shimanoe, N. Yamazoe, NASICON-based potentiometric CO2 sensor combined with new materials operative at room temperature, *Sensors and Actuators B*, **108** 352–358 (2005)

Appendix A5
Table A5. Sensors for Relative Humidity

Principle	Manufacturer / Supplier	Instrument(s)	References	Notes
COTS				
Cap	Airtest	various	A5.1	
Cap	Quest Technologies	AQ 5000 Pro, AQ 5001 Pro	A5.2	
Cap	TSI	Q-Trak 8552,-PlusQ-Trak 8554-Plus with CO, Q-Trak 7565	A5.3-4	thin film
Cap	YES Environment Technologies	YES-205, YESair, YESplus	A5.5-7	thin film
IR	Licor	LI-7000 CO2/H2O Analyzer	A5.8	
Psychr	TSI	wet bulb psychrometer; TH-Calc series	A5.9	thin film
Var	TSI	Q-trak, Q-trak Plus 8554	A5.10	
Var	TSI	IAQ instruments list	A5.11	
Unknown	Vaisala	HHM30C	A5.12	
Research				
CNT	Penn State University	research	A5.13	resistance change of MWCNT
MOS	Indian university	research	A5.14	resistance change of nano-structured ZnO

References - Appendix A5
Table A5. Sensors for Relative Humidity

Ref	Pdf	Reference
COTS		
A5.1	AirTest RH guide 2009.pdf	*https://www.airtesttechnologies.com/support/reference/indrhguide.pdf*
A5.2	Quest-IAQ-2009.pdf	*http://questtechnologies.com/QuestFiles/61/QuestIAQ.pdf*
A5.3	q-trak.pdf	*http://www.tsi.com/uploadedFiles/Product_Information/Literature/Spec_Sheets/qtrak.pdf*
A5.4	TSI-7565_Q-trak_298057D_USA.pdf	*http://www.tsi.com/uploadedFiles/Product_Information/Literature/Spec_Sheets/7565_Q-Trak_2980572D_USA.pdf*
A5.5	yes205literature.pdf, YES205-Manual.pdf	*http://www.yestek.com/PDF/yes205literature.pdf, http://www.yestek.com/PDF/YES205-Manual.pdf*
A5.6	YESair_literature.pdf	*http://www.yestek.com/PDF/YESair_literature.pdf*
A5.7	YESplus_literature.pdf	*http://www.yestek.com/PDF/YESplus_literature.pdf*
A5.8	LI7000.pdf	*http://www.licor.com/env/PDF/LI7000.pdf*
A5.9	TSI-2980576-7415-7425-TH-Calc.pdf	*http://www.tsi.com/uploadedFiles/Product_Information/Literature/Spec_Sheets/2980576-7415-7425-TH-Calc.pdf*
A5.1	TSI-Q-Trak Plus IAQ monitor-1980417I.pdf	*http://www.tsi.com/uploadedFiles/Product_Information/Literature/Manuals/1980417I.pdf*
A5.11	TSI-Indoor-Air-Quality-Handbook-2009.pdf	*http://www.ecoenvironmental.com.au/eco/downloads/dust_General_Indoor_Air_Quality_Measurements.pdf*
A5.12	Final Report-1262-RP-Batelle.pdf	C.W. Spicer, M.J. Murphy, M.W. Holdren, J.D. Myers, I.C. MacGregor, C. Holloman, R.R. James, K.Tucker and R. Zaborski, Relate Air Quality and Other Factors to Comfort and Health Symptoms Reported by Passengers and Crew on Commercial Transport Aircraft (Part I) (ASHRAE Project 1262-TRP), Final Report to American Society for Heating, Refrigerating and Air Conditioning Engineers, 337 pp. (2004)

Research		
A5.13	Varghese 2001-CO.pdf	O.K. Varghese, P.D. Kichambre, D. Gong, K.G. Ong, E.C. Dickey, C.A. Grimes, Gas sensing characteristics of multi-wall carbon nanotubes, *Sensors and Actuators B,* **81**, 32-41 (2001)
A5.14	Yadav H2O-2008.pdf	B.C. Yadav, R. Srivastava, C.D. Dwivedi and P. Pramanik, Moisture sensor based on ZnO nanomaterial synthesized through oxalate route, *Sensors and Actuators B*, **131** 216–222 (2008)

Appendix B

(Figures B1-B8)

Equipment Configuration during Chamber Experiments

Figure B1. Ozone: Changing Pressure (Experiments 1-5)

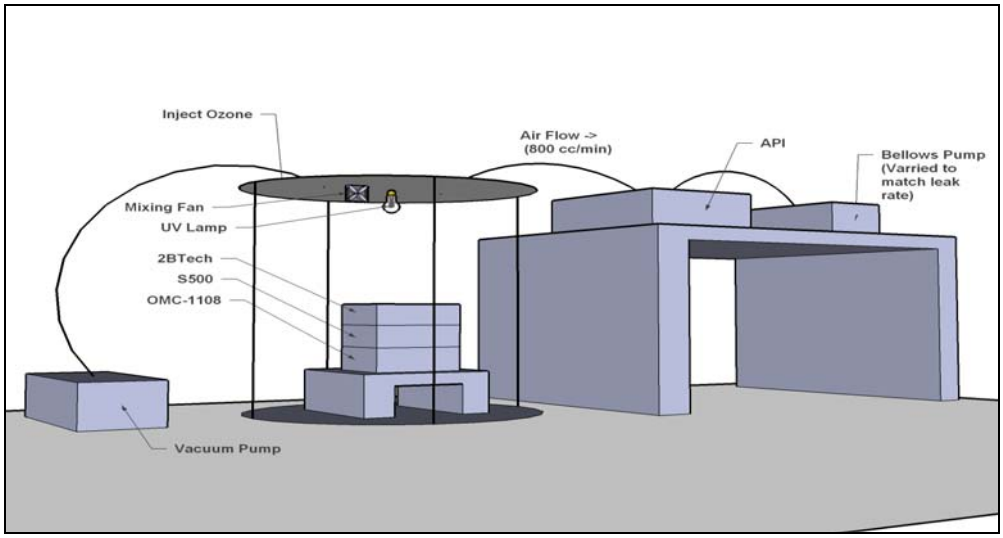


Figure B2. CO/CO_2: Changing Pressure (Experiments 6-9)

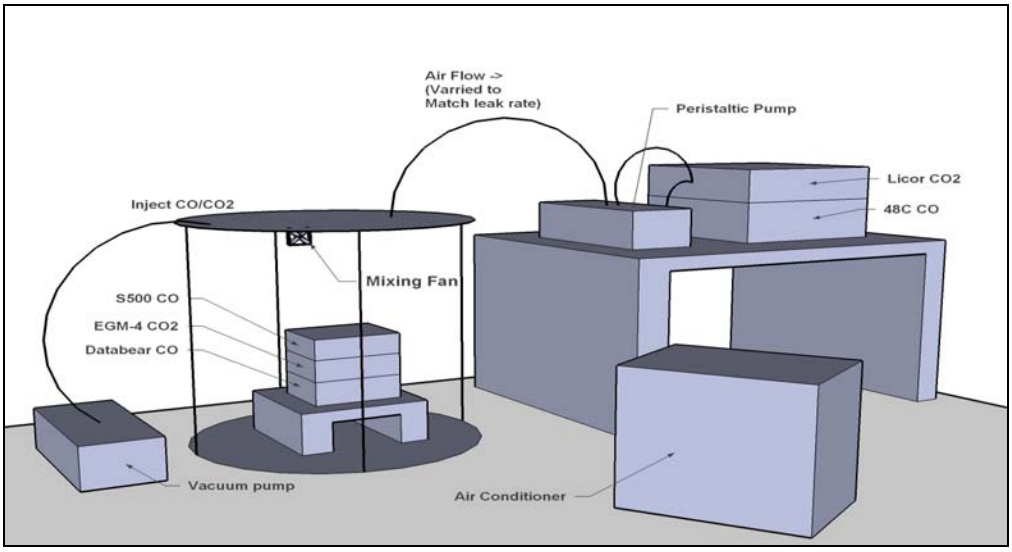


Figure B3. CO/CO_2: Changing Pressure (Experiments 10-14)

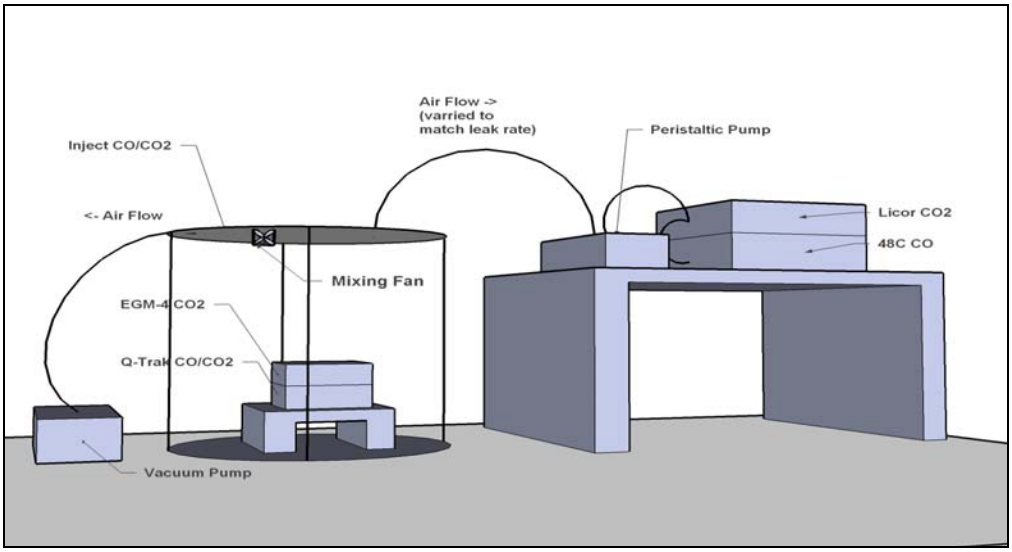


Figure B4. Ozone: Changing Humidity (Experiments 15-20)

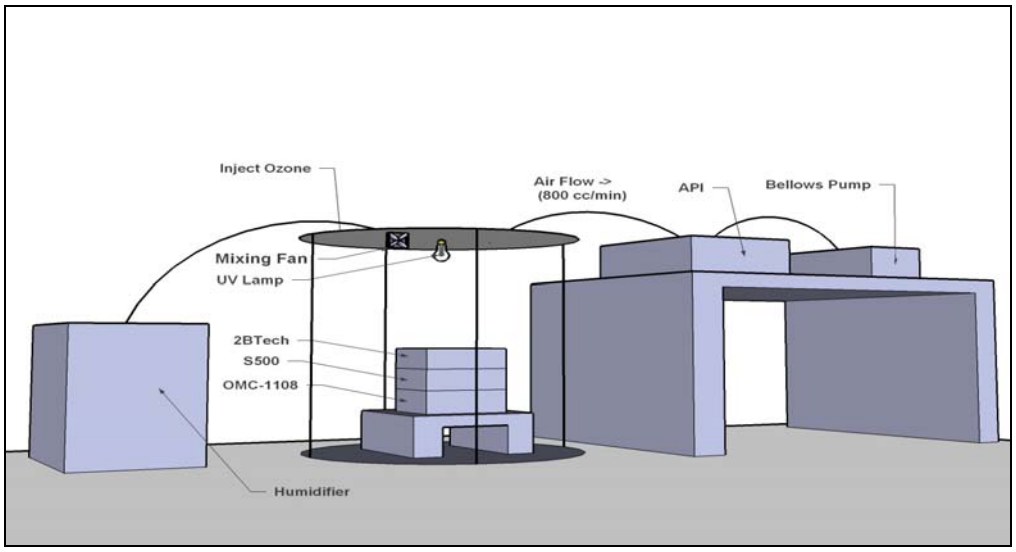


Figure B5. CO/CO_2: Changing Humidity (Experiments 21-24)

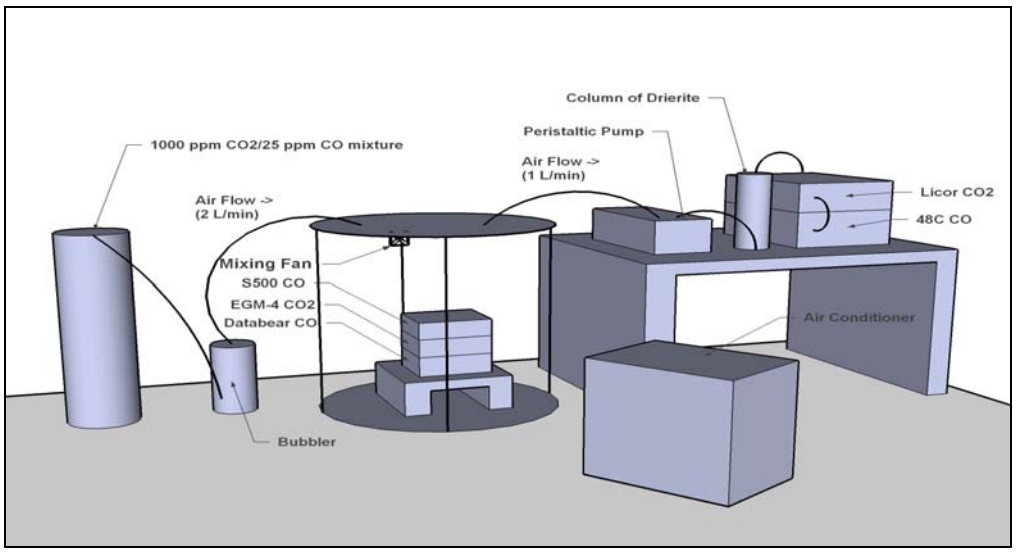


Figure B6. Ozone: Changing Temperature (Experiments 25-26)

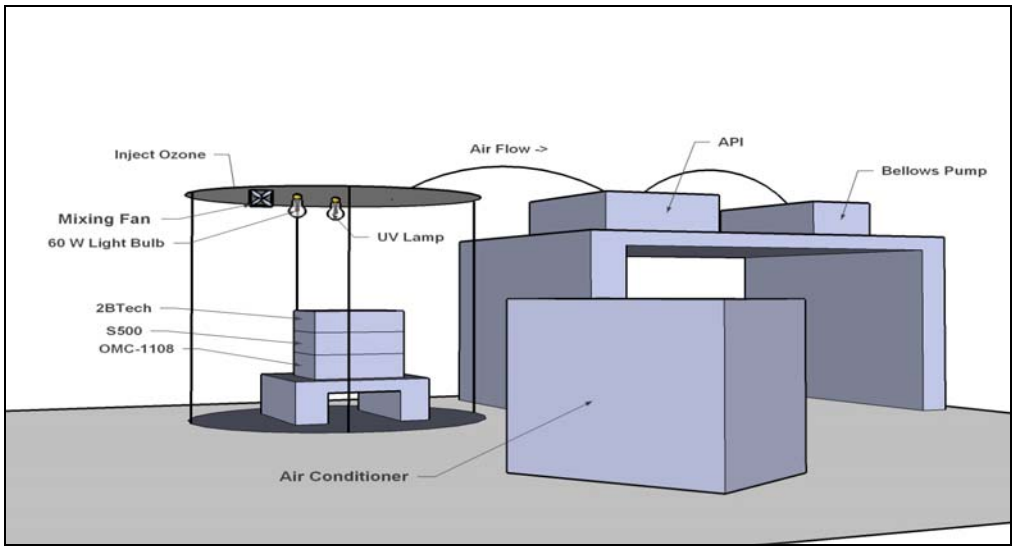


Figure B7. CO/CO_2: Changing Temperature (Experiments 27-31)

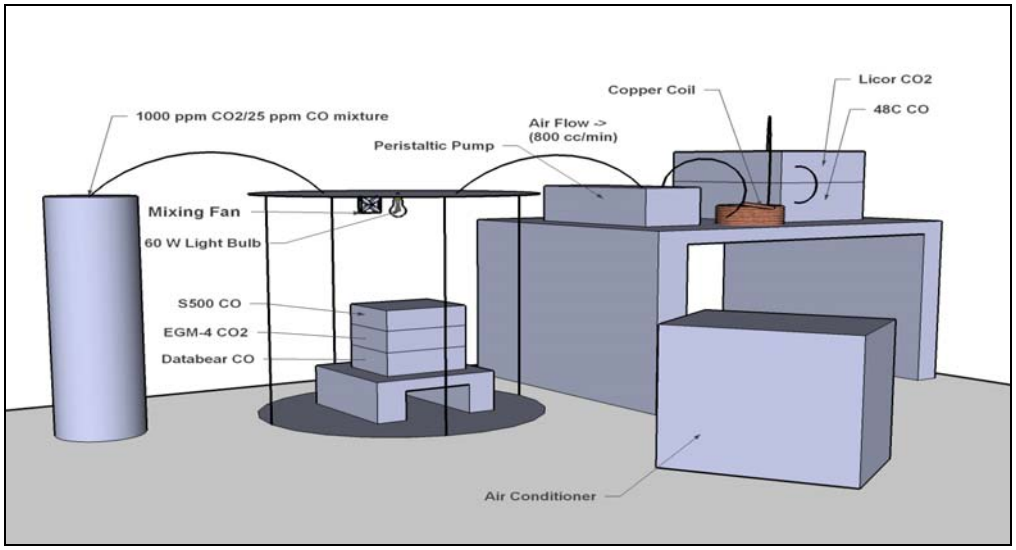
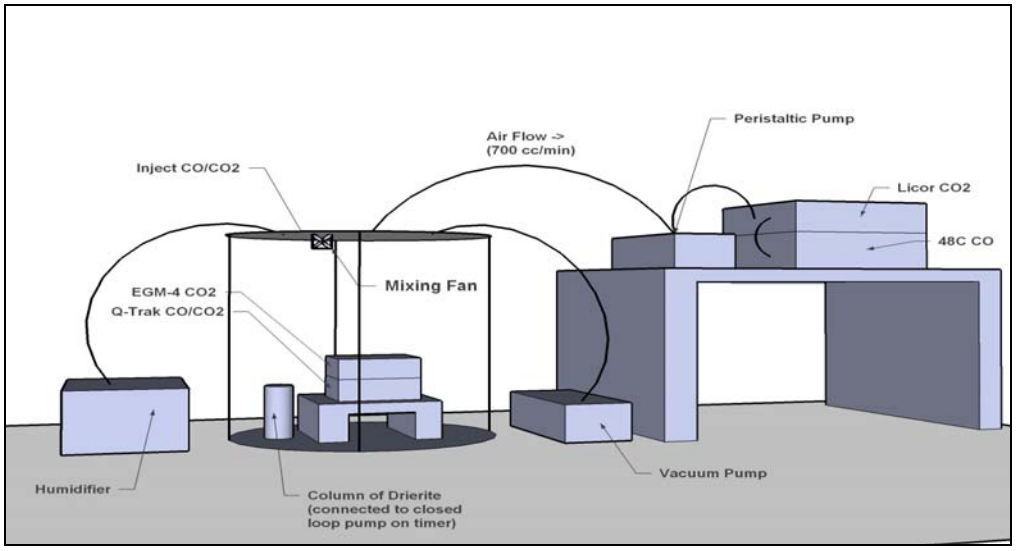


Figure B8. CO/CO_2: Changing Temperature and Humidity (Experiments 32-34)



Appendix C

(Figures C1-C8)

Time Series of Pressure, Temperature, Relative Humidity and Water Vapor Pressure during Chamber Experiments

Figure C1. Changing Pressure, Experiments 1-5, Ozone Analyzers

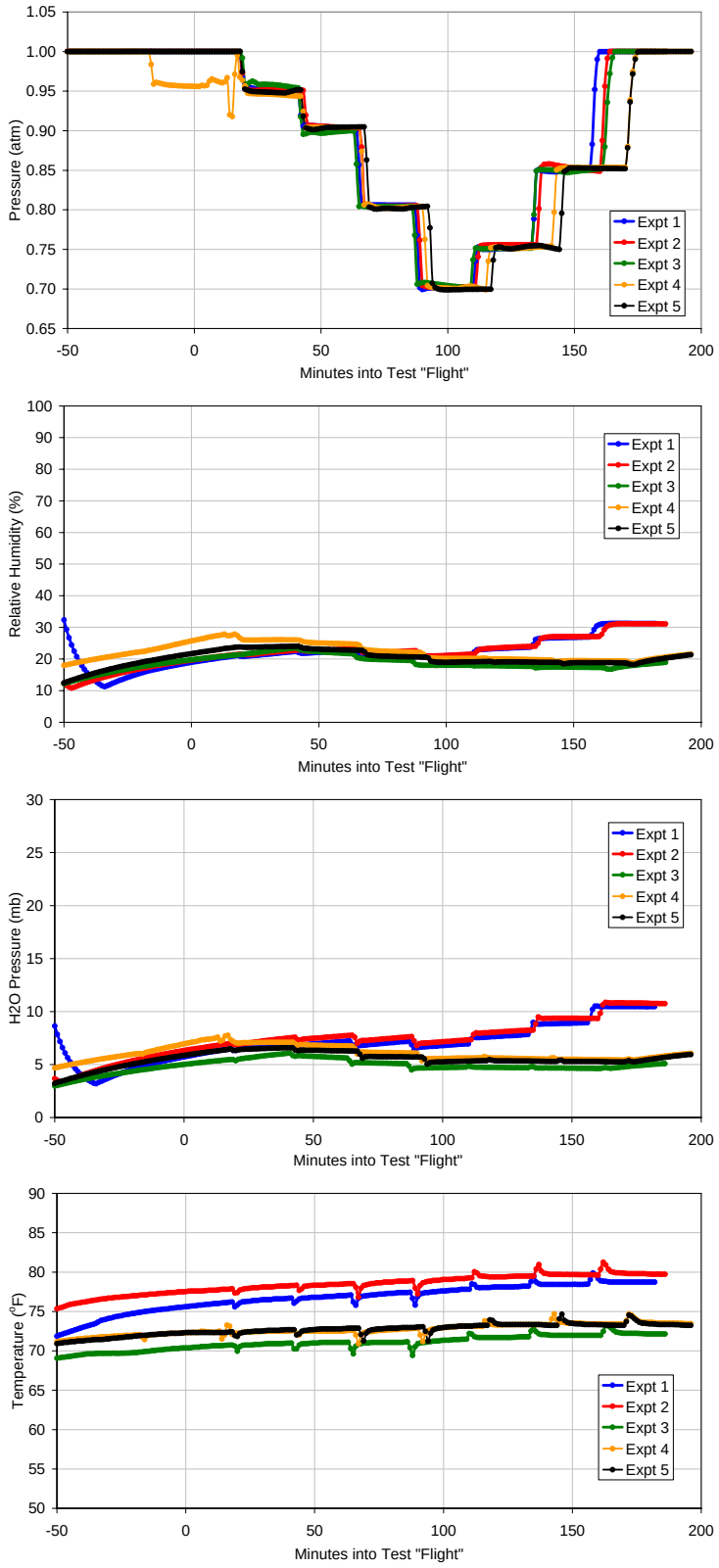


Figure C2. Changing Pressure, Experiments 6-9, CO/CO_2 Analyzers

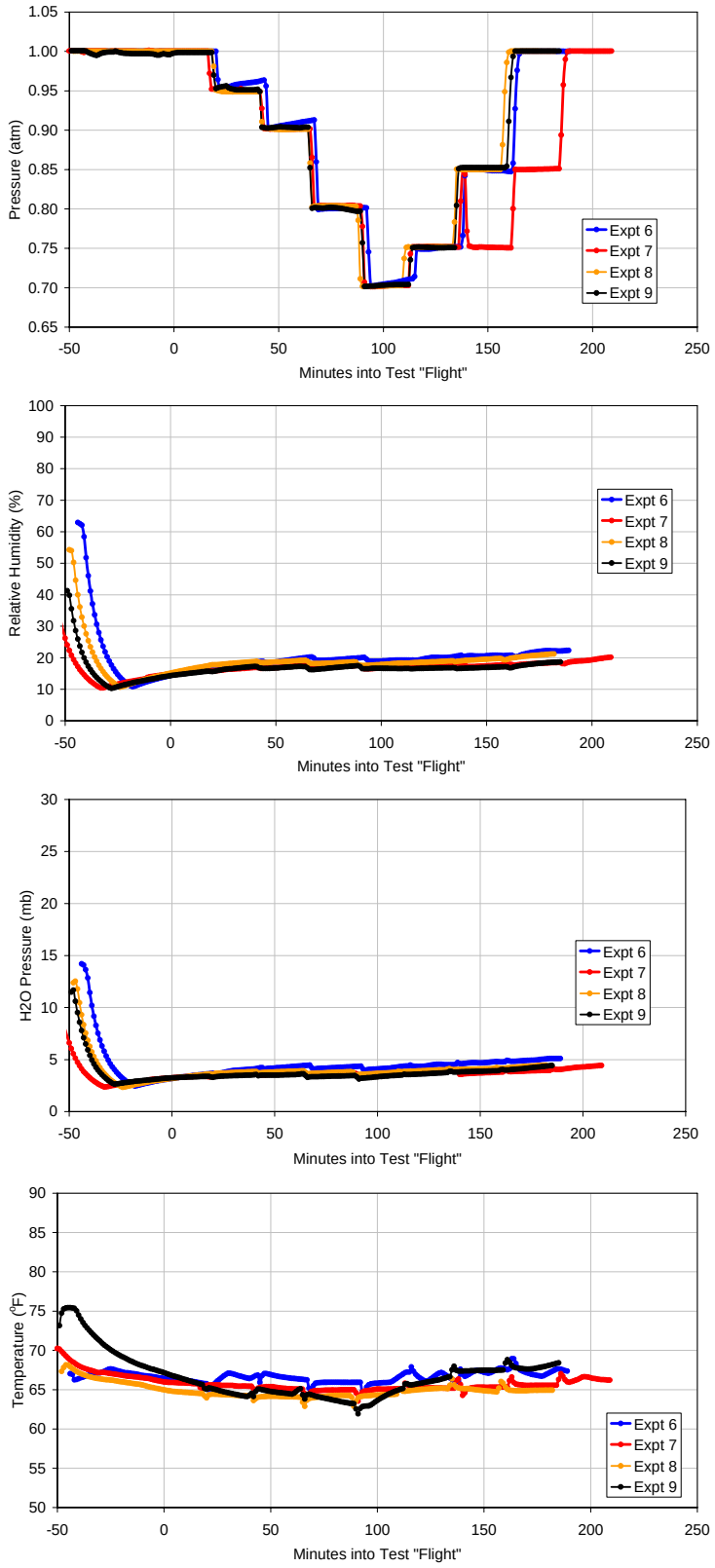


Figure C3. Changing Pressure, Experiments 10-14, CO/CO_2 Analyzers

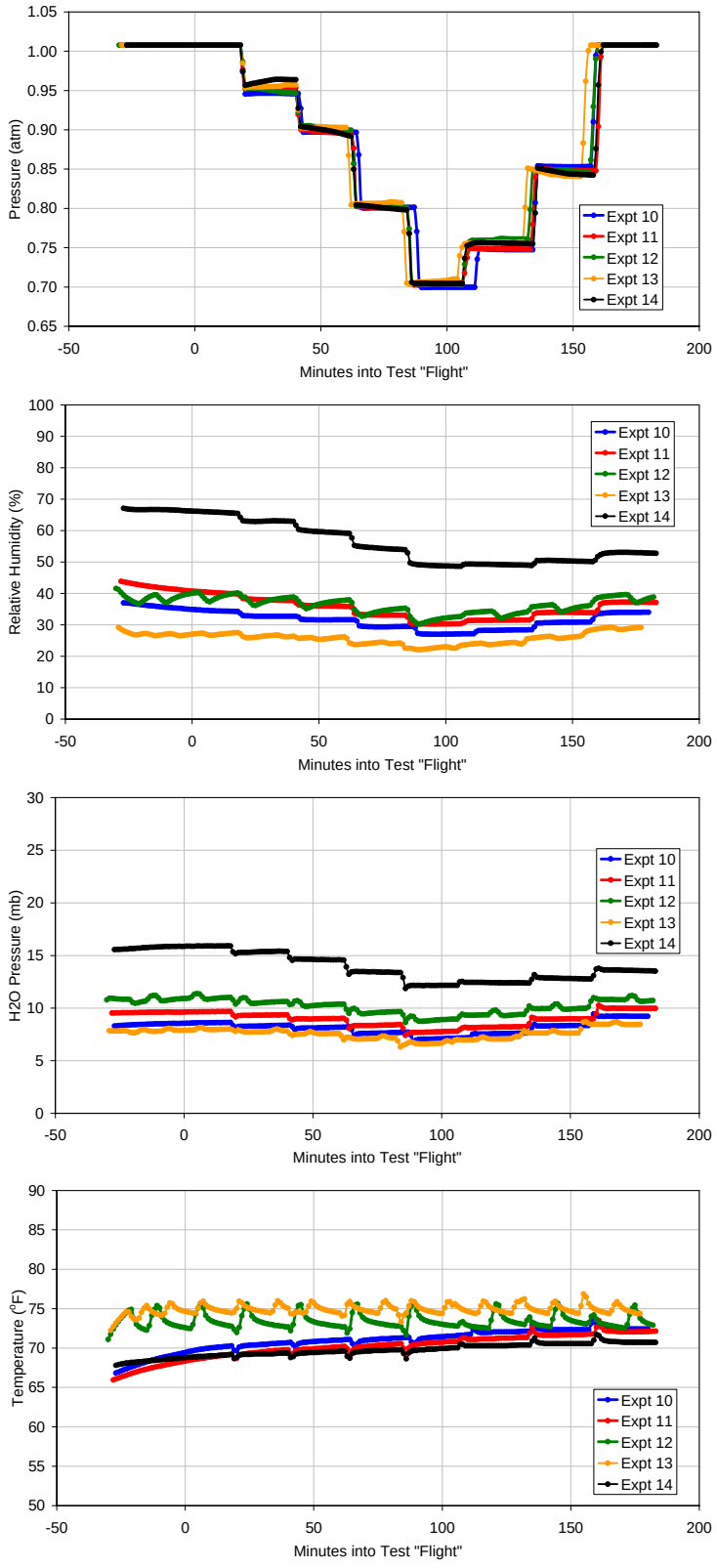


Figure C4. Changing Humidity, Experiments 15-20, Ozone Analyzers

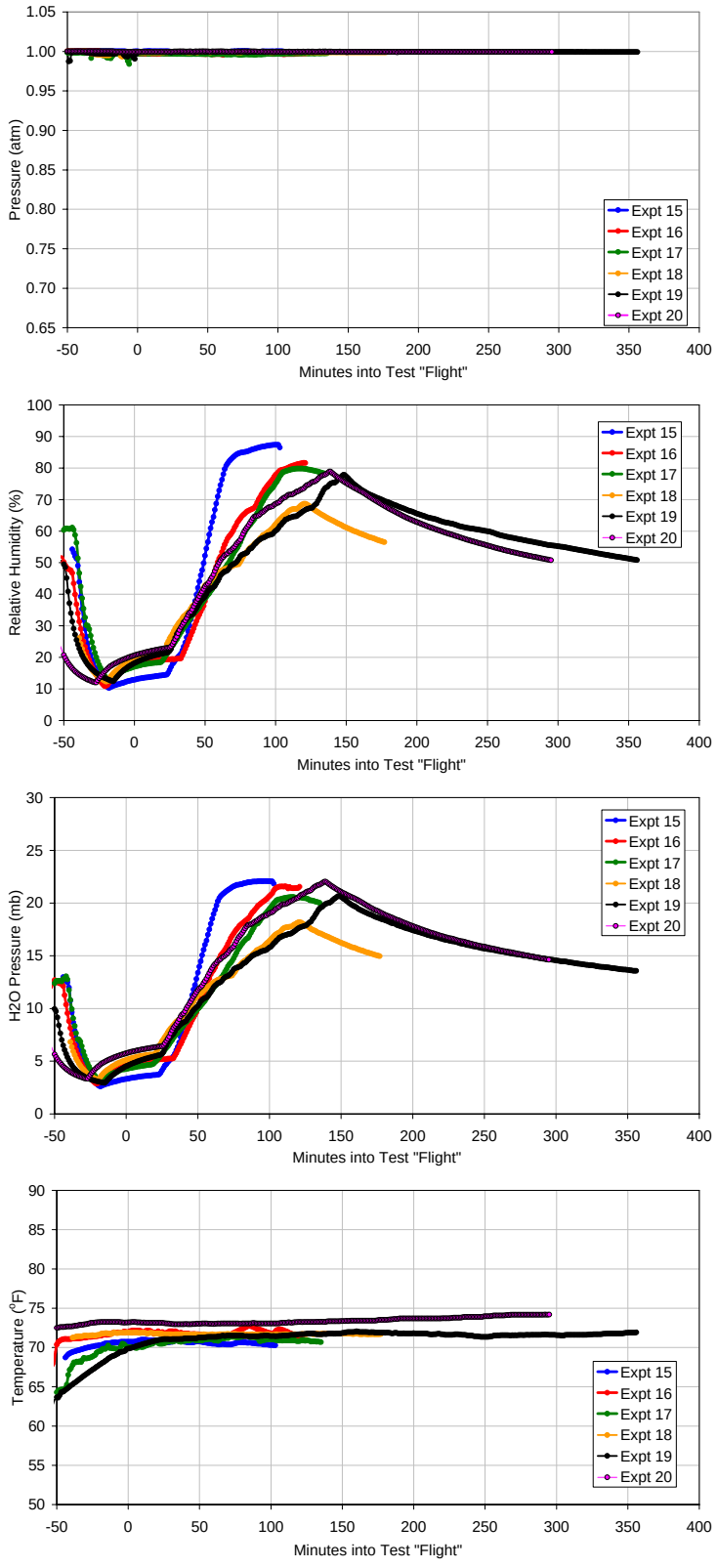
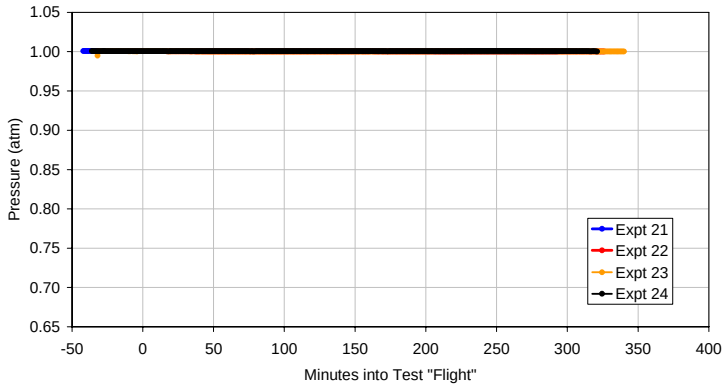
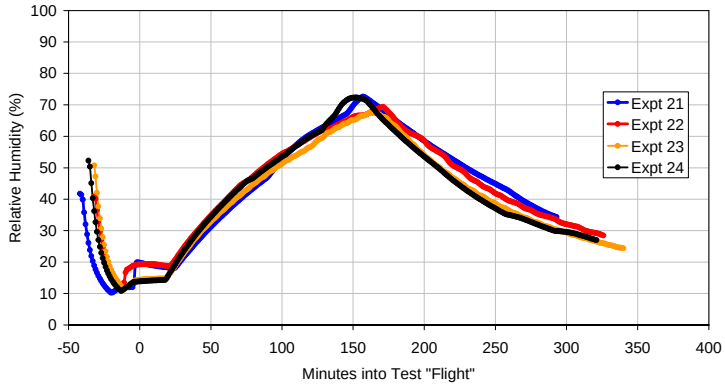
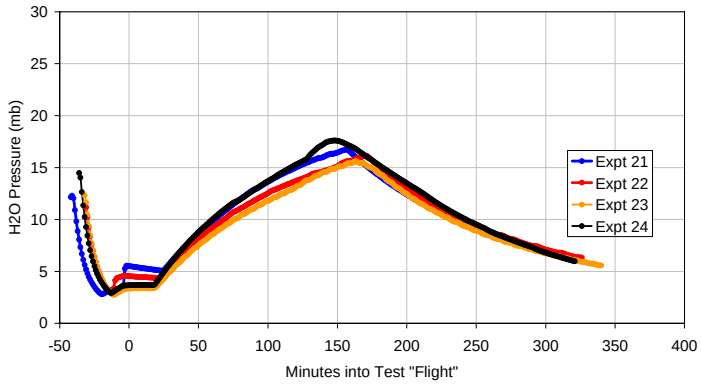


Figure C5. Changing Humidity, Experiments 21-24, CO/CO_2 Analyzers







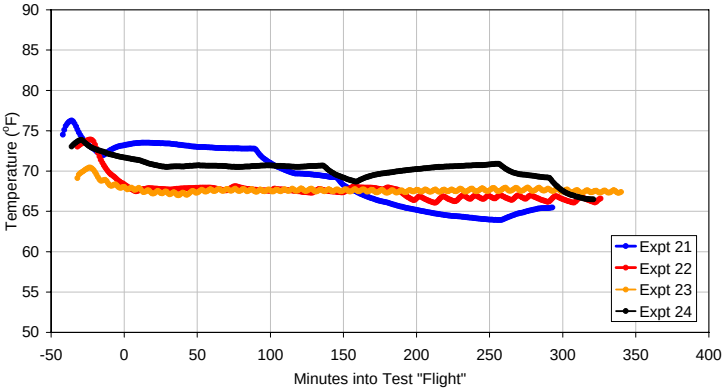


Figure C6. Changing Temperature, Experiments 25-26, Ozone Analyzers

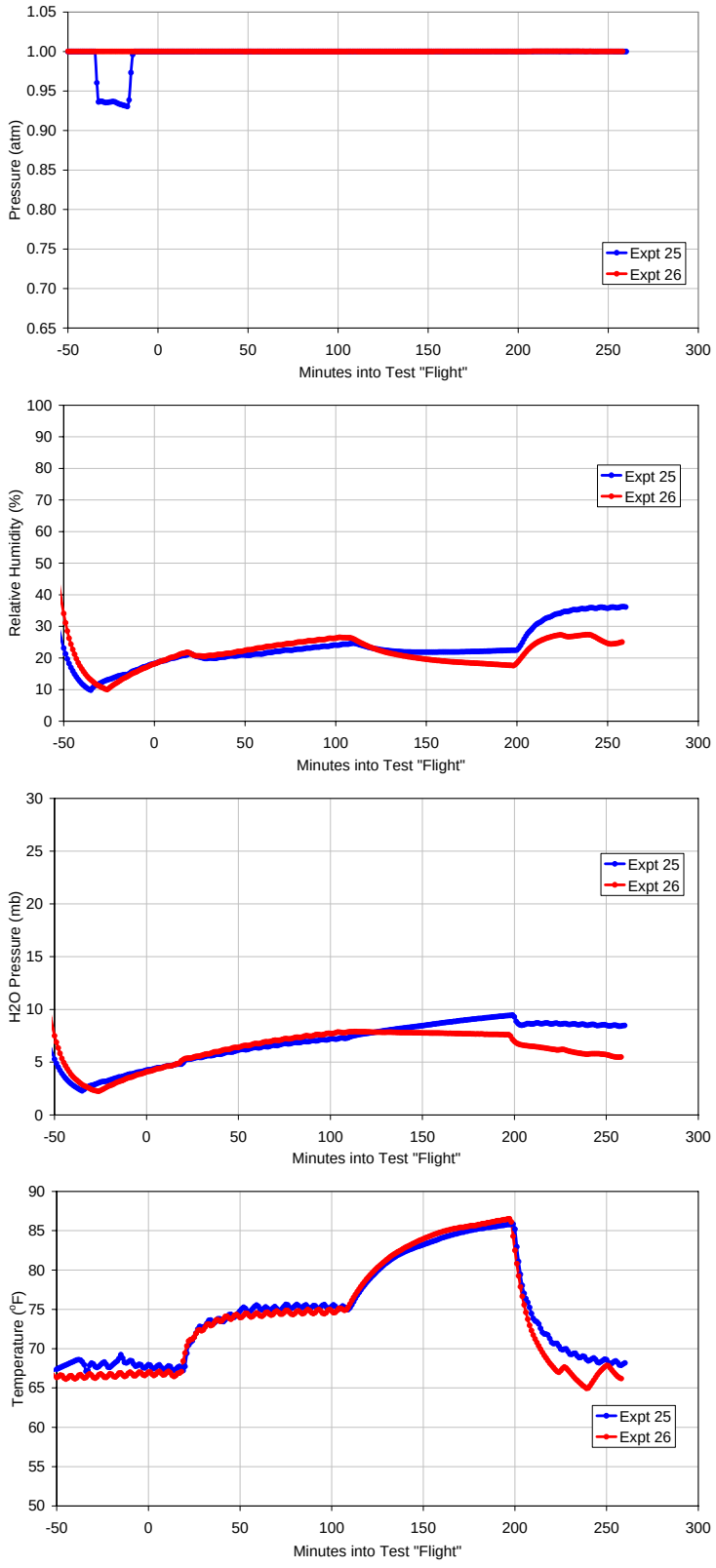


Figure C7. Changing Temperature, Experiments 27-31, CO/CO_2 Analyzers

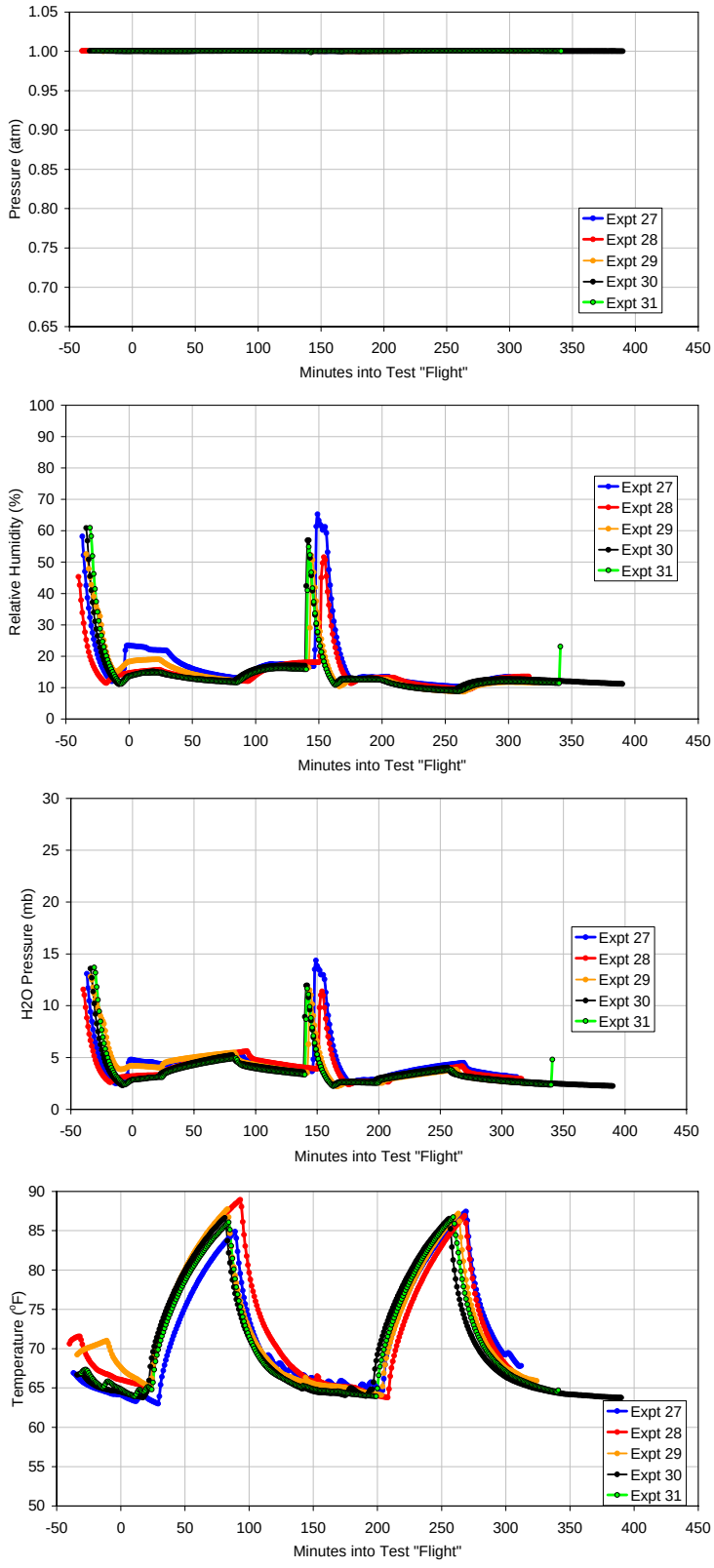
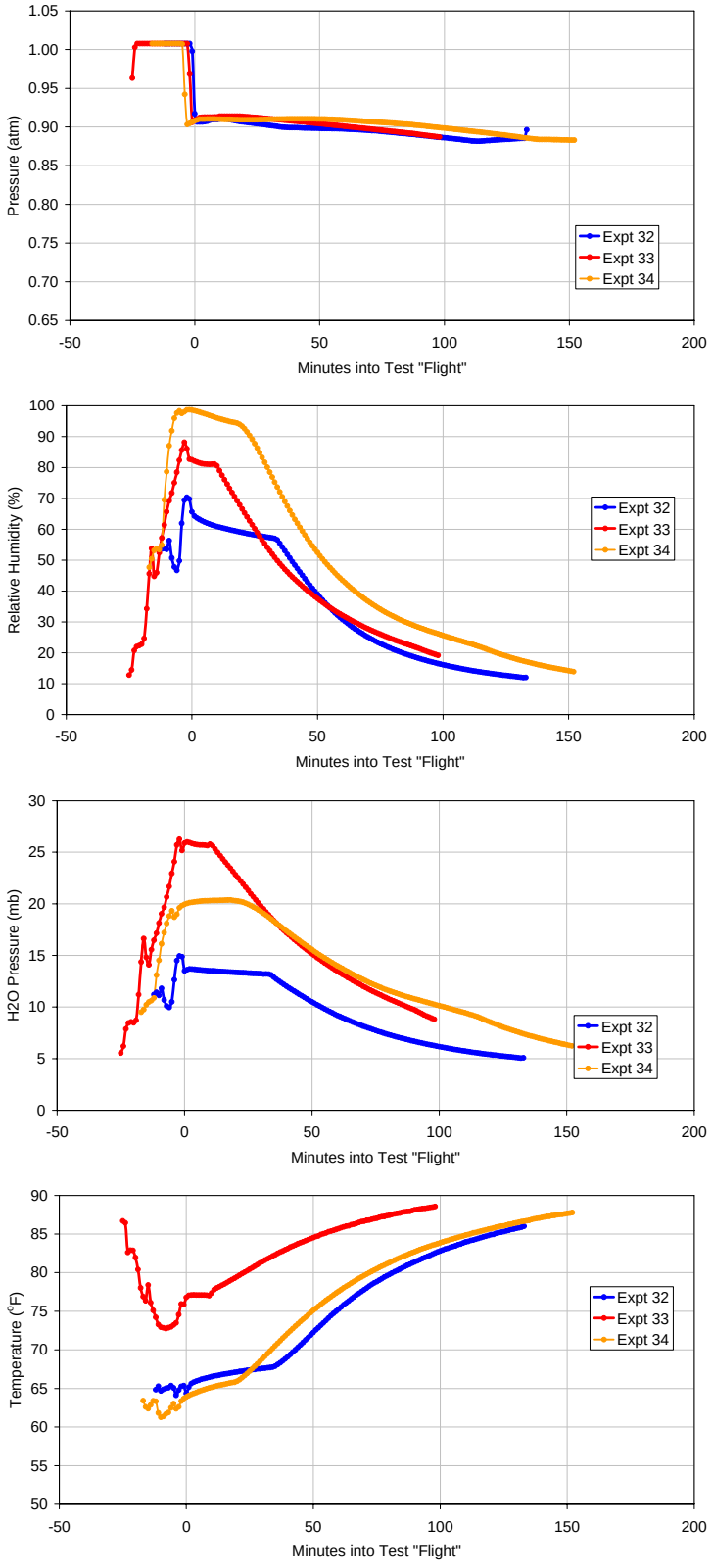


Figure C8. Changing Temperature + Humidity, Experiments 32-34, CO/CO_2 Analyzers

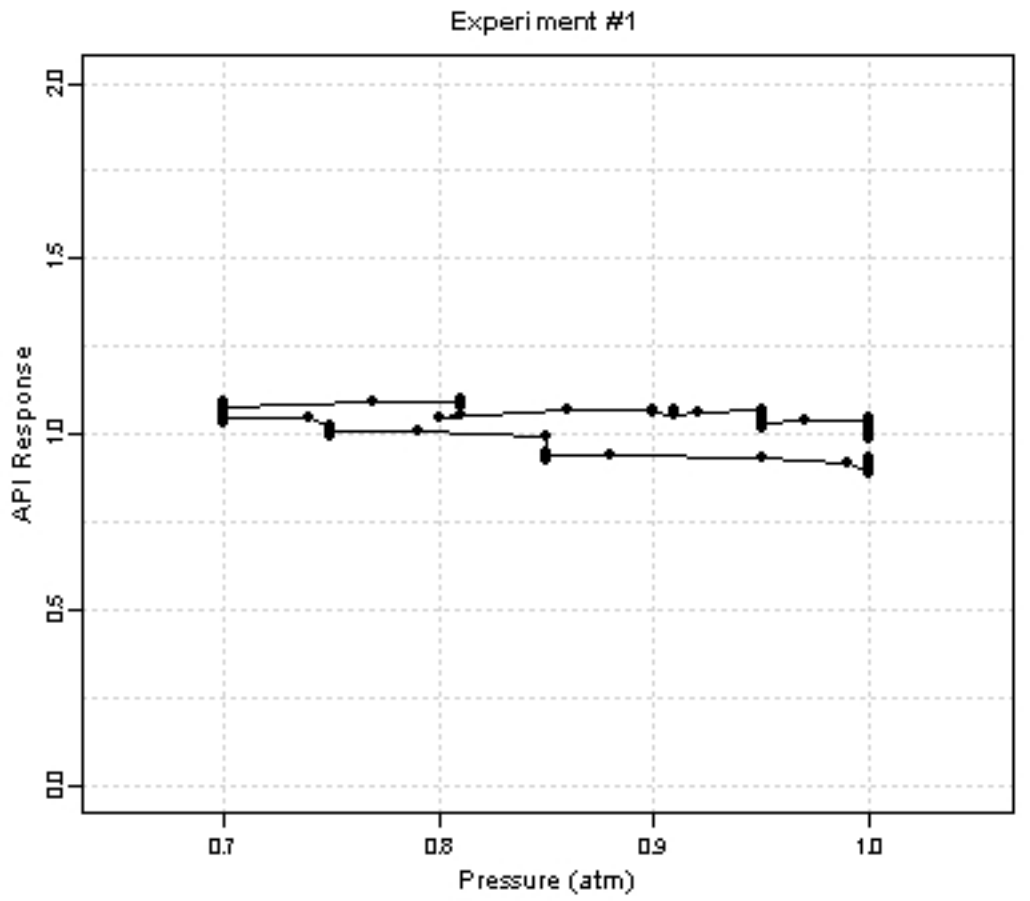


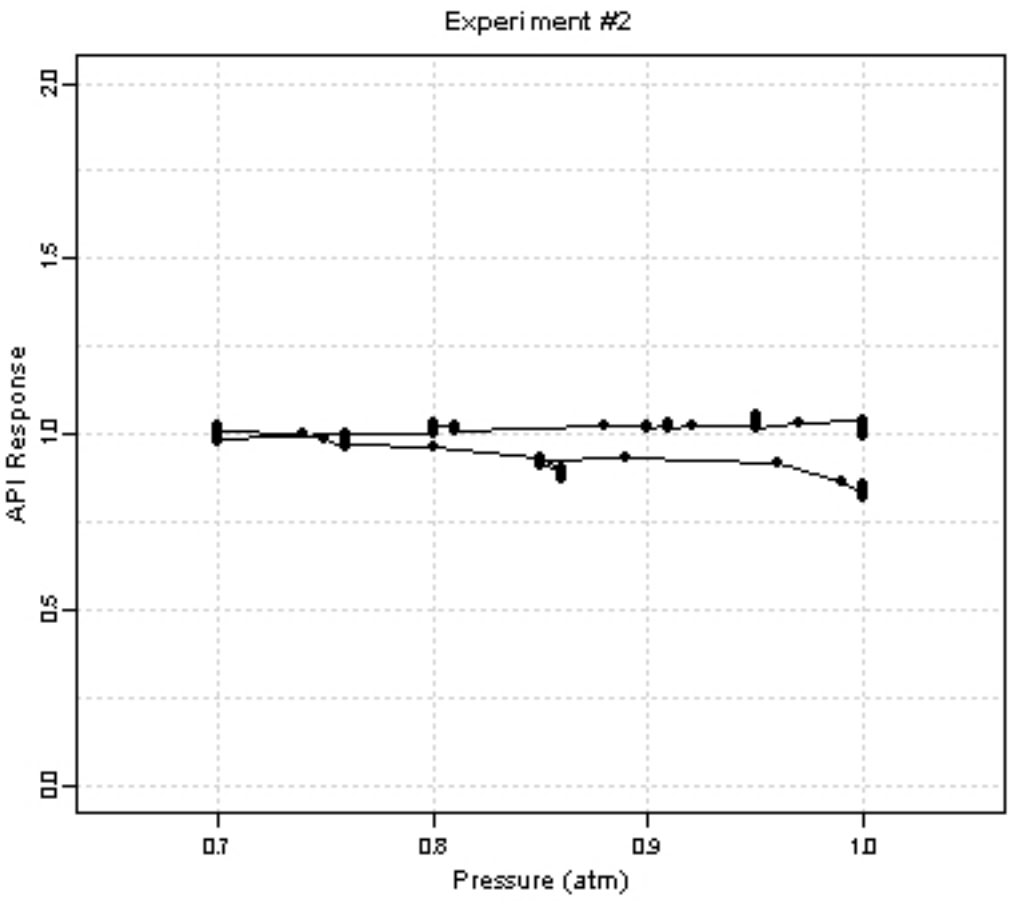
Appendix D

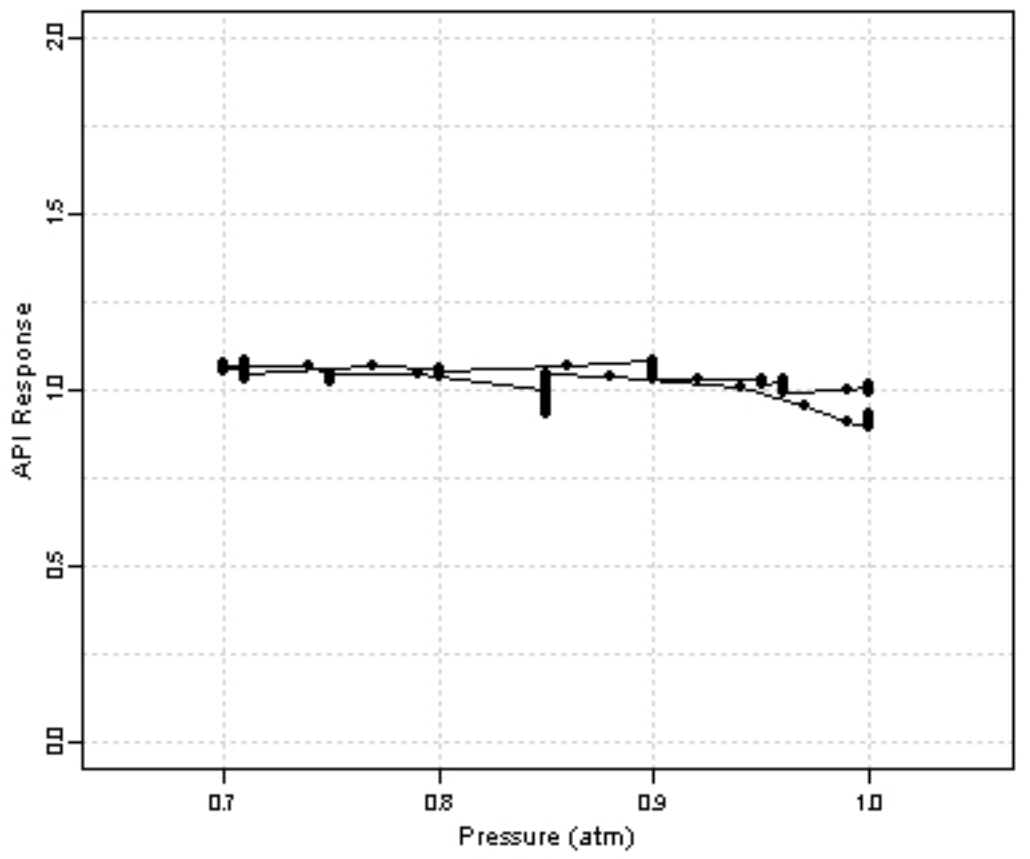
(Figures D1-D44)

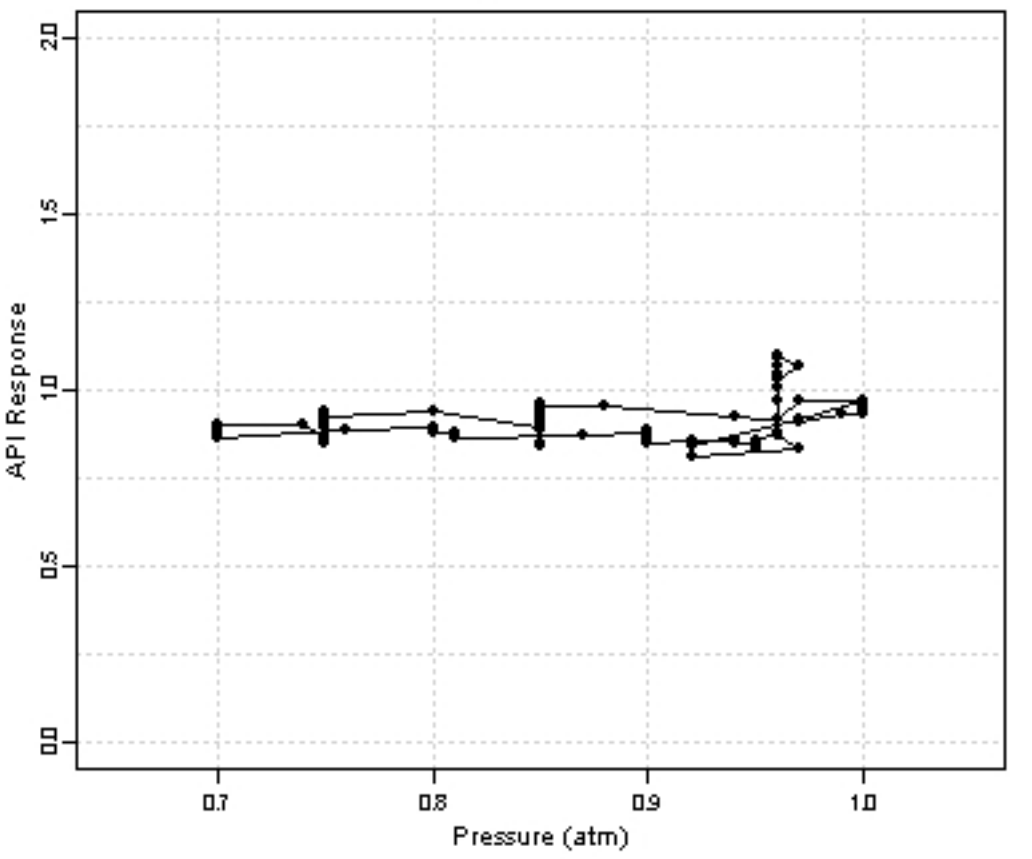
Response of Each Instrument during Chamber Experiments

Fig. D1 Ozone Tests: Variable Pressure: API/API (Expts 1-5)









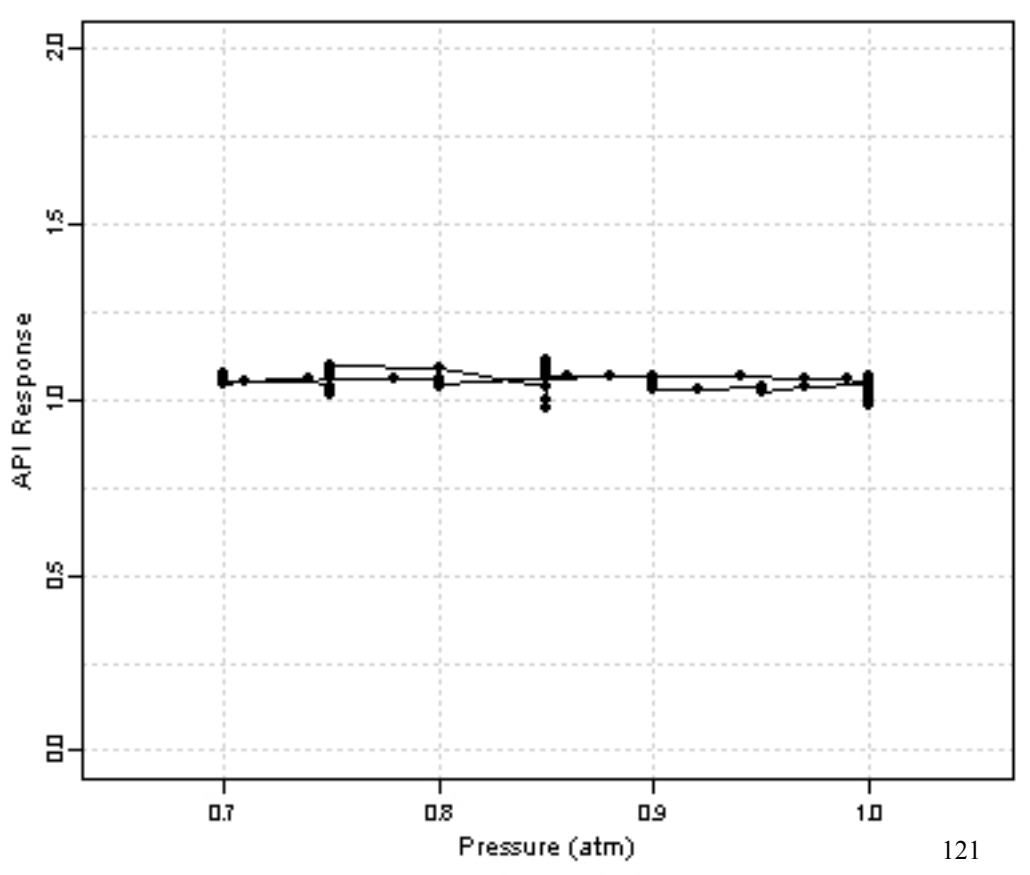
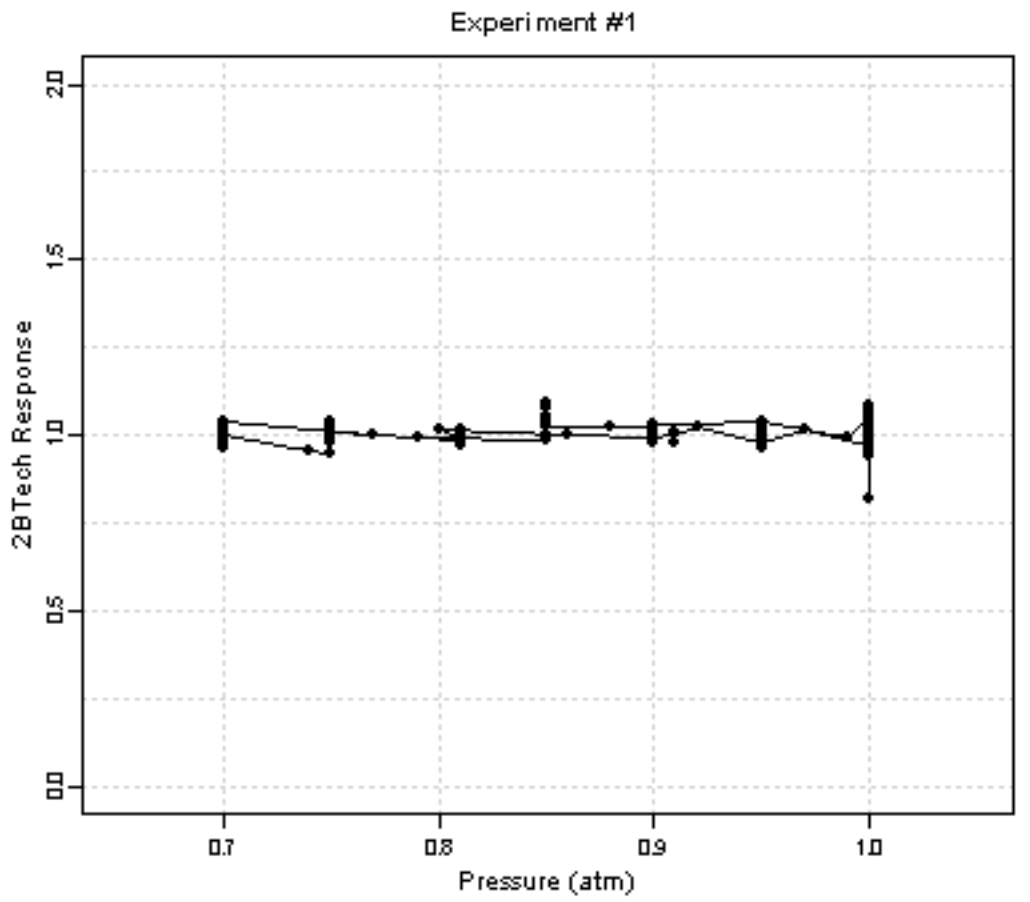
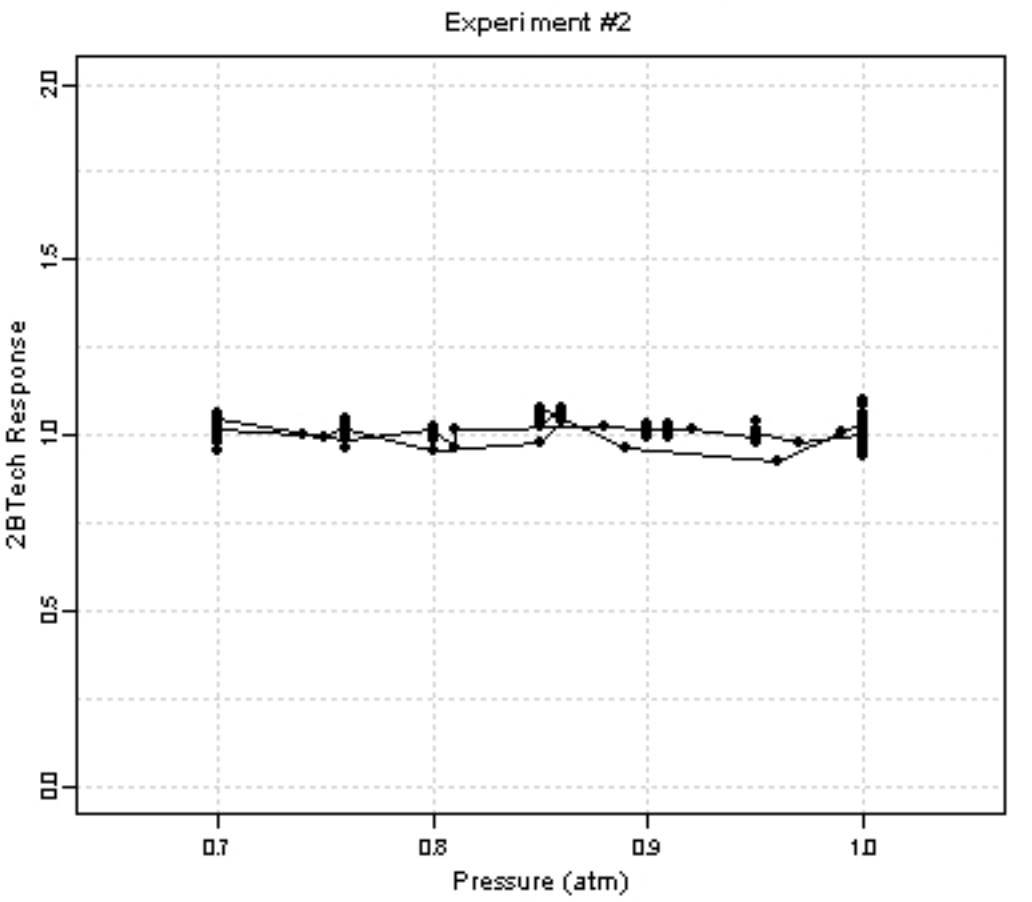
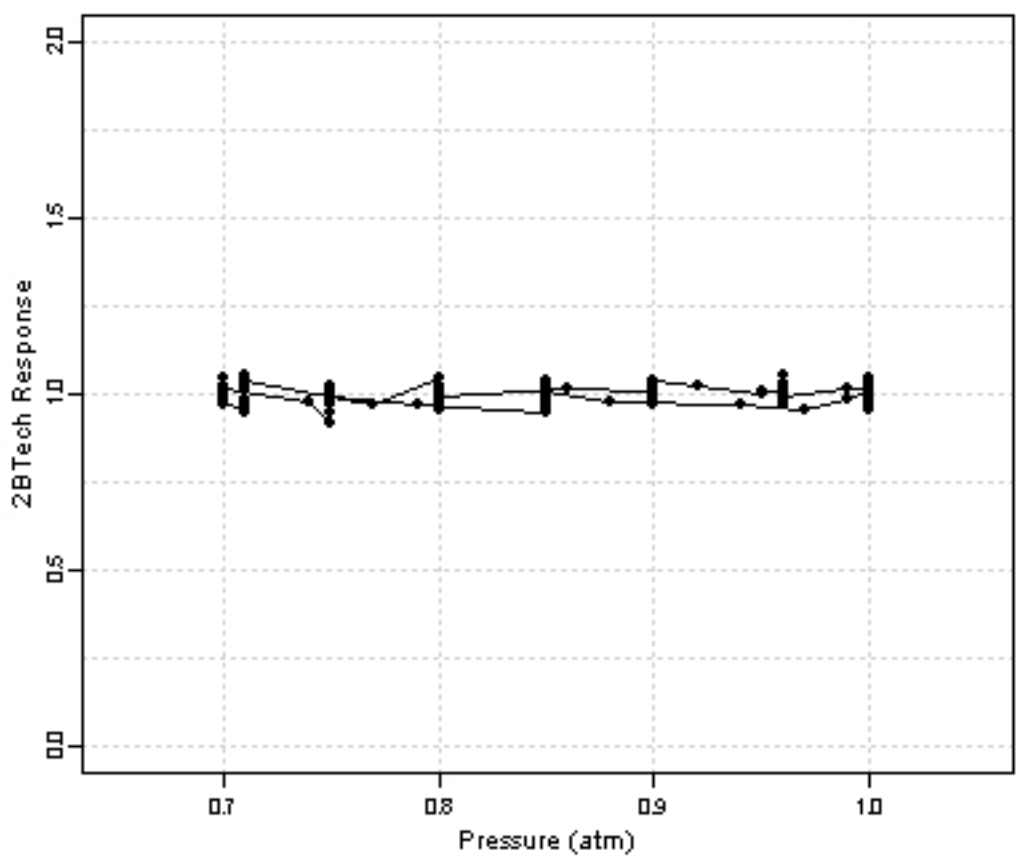
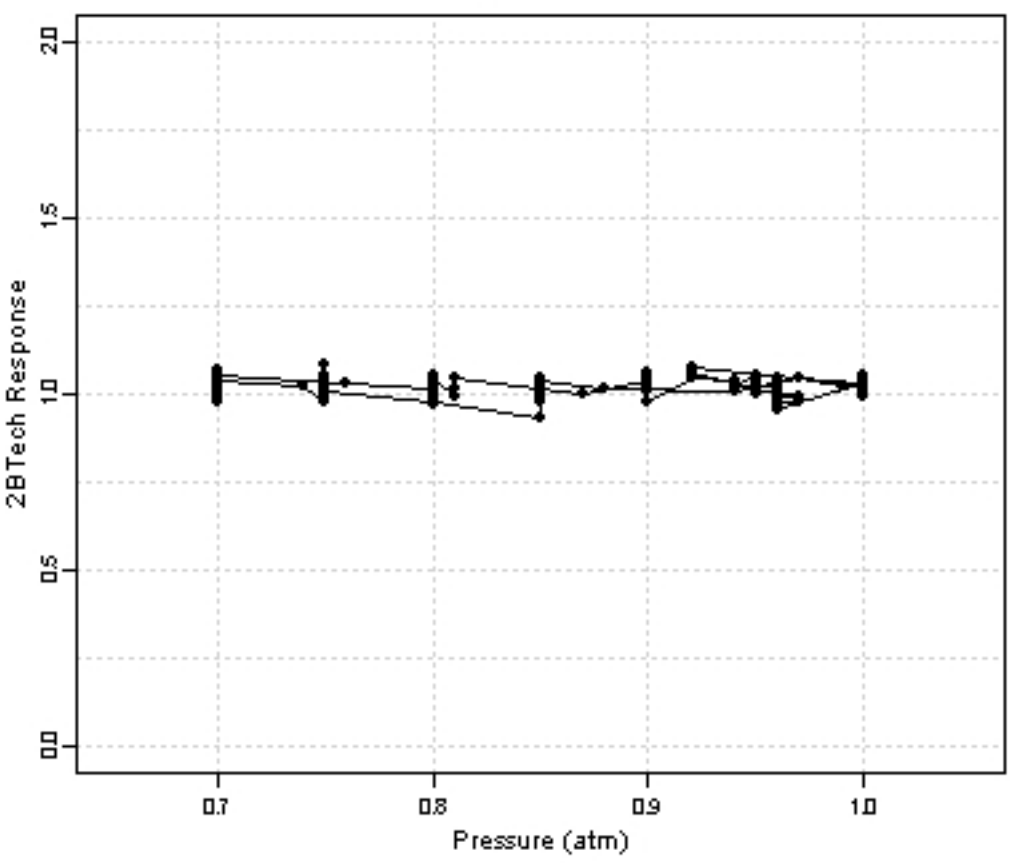


Fig. D2 Ozone Tests: Variable Pressure: 2BTech/API (Expts 1-5)









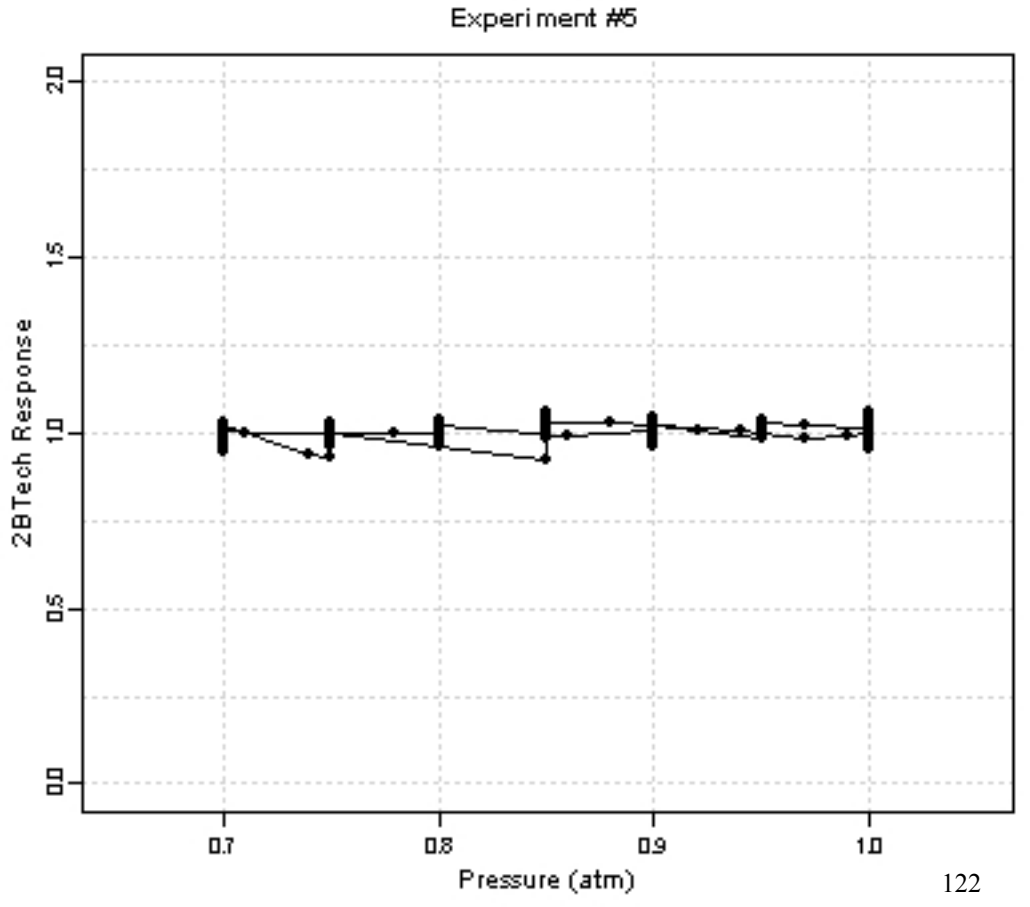
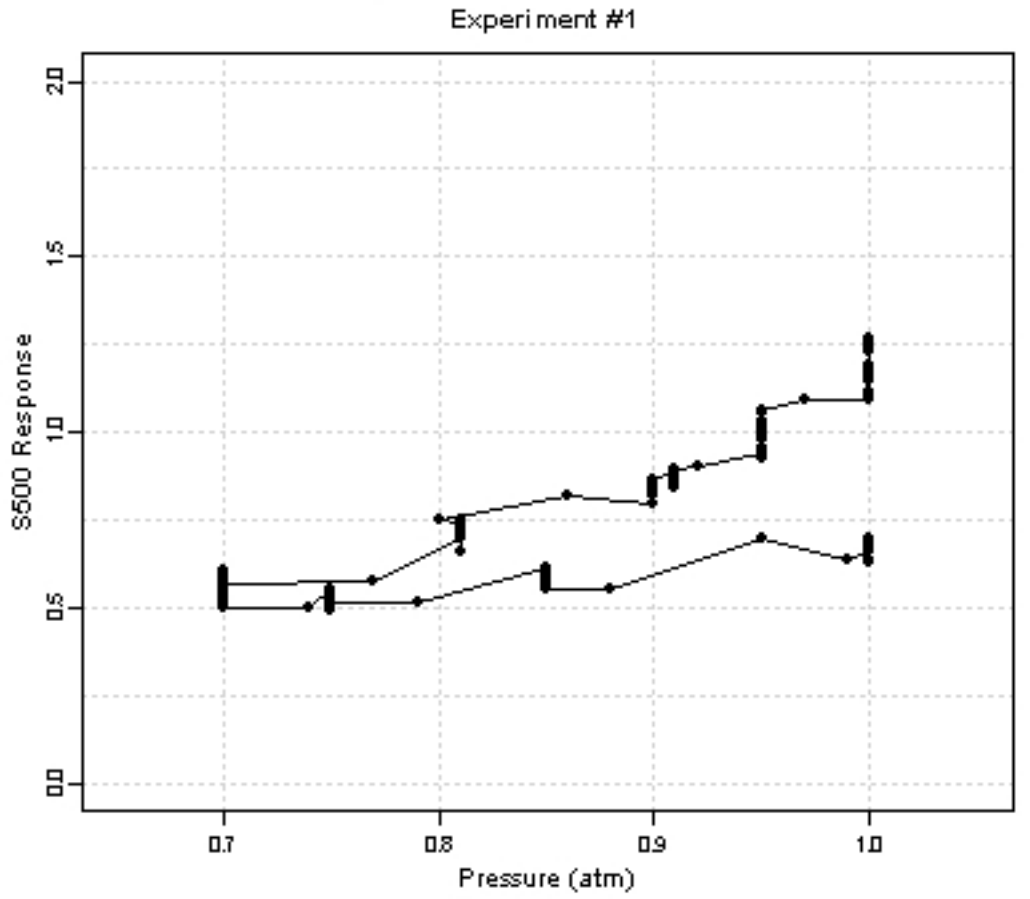
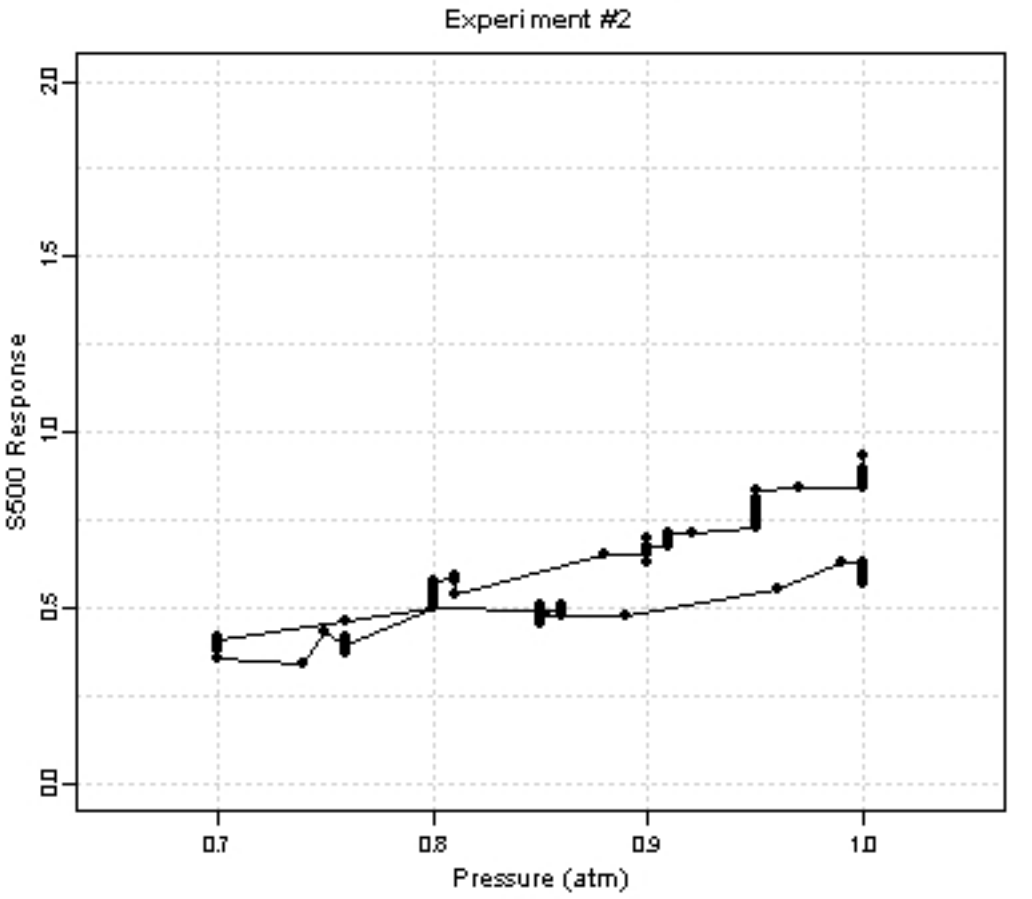
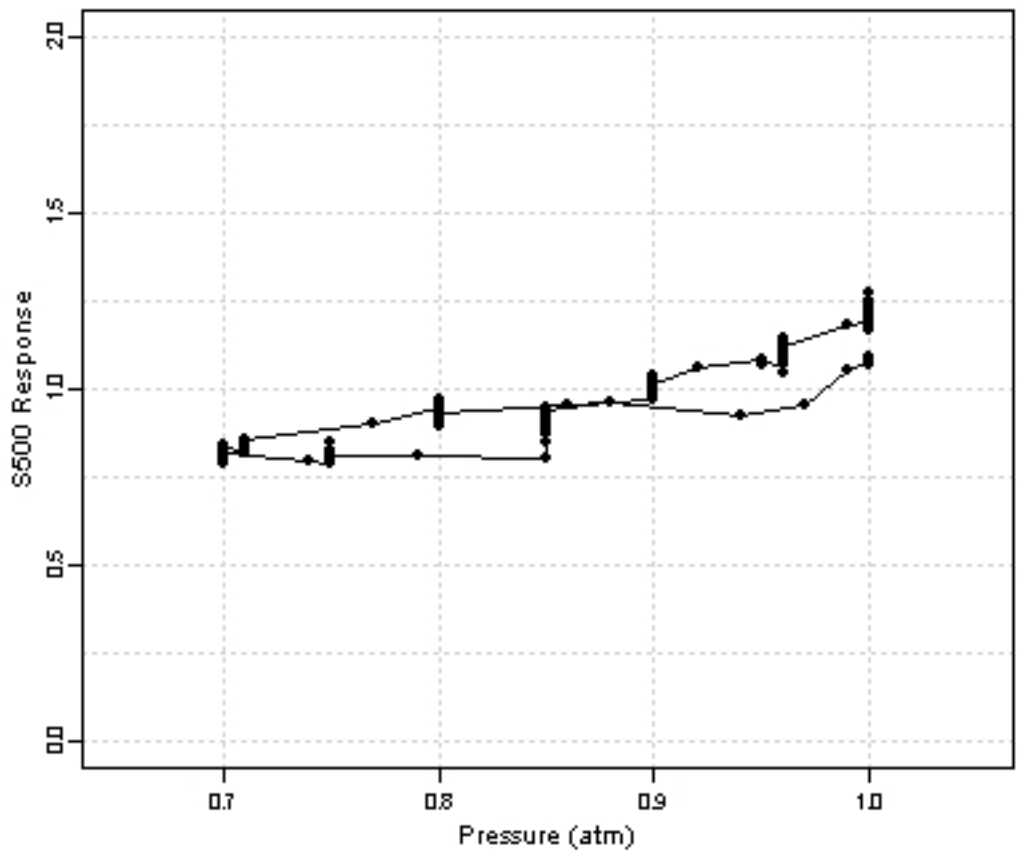
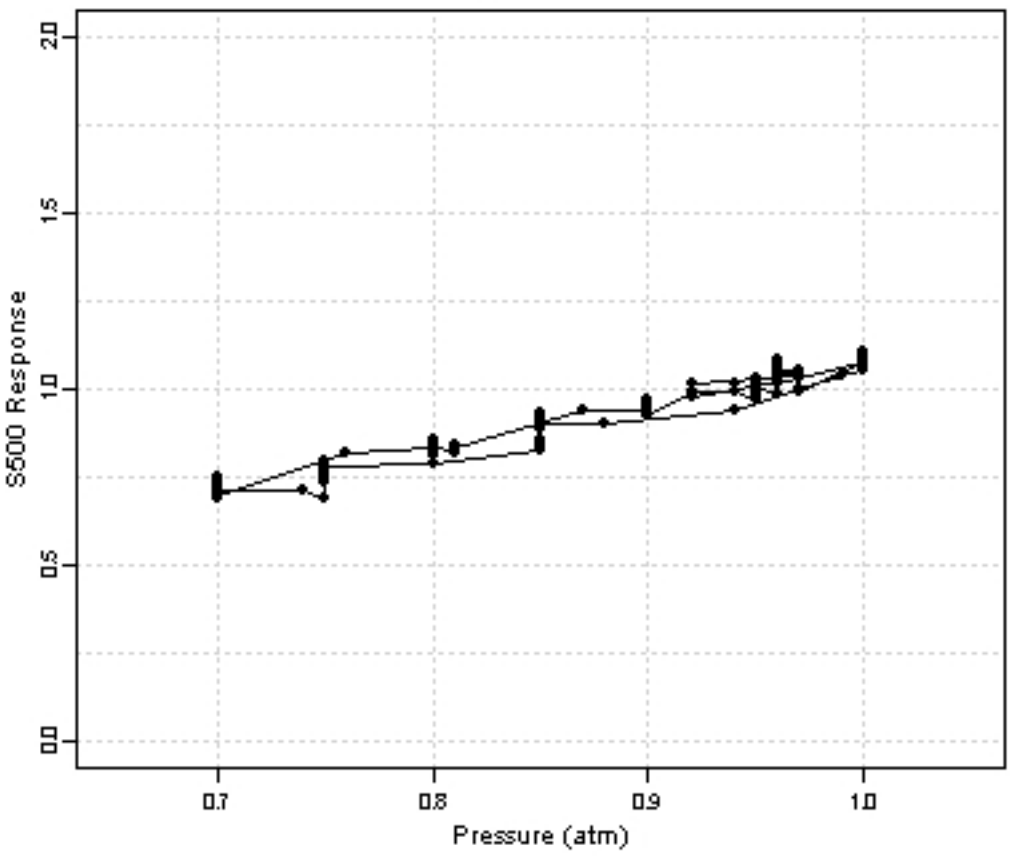


Fig. D3 Ozone Tests: Variable Pressure: S500/API (Expts 1-5)









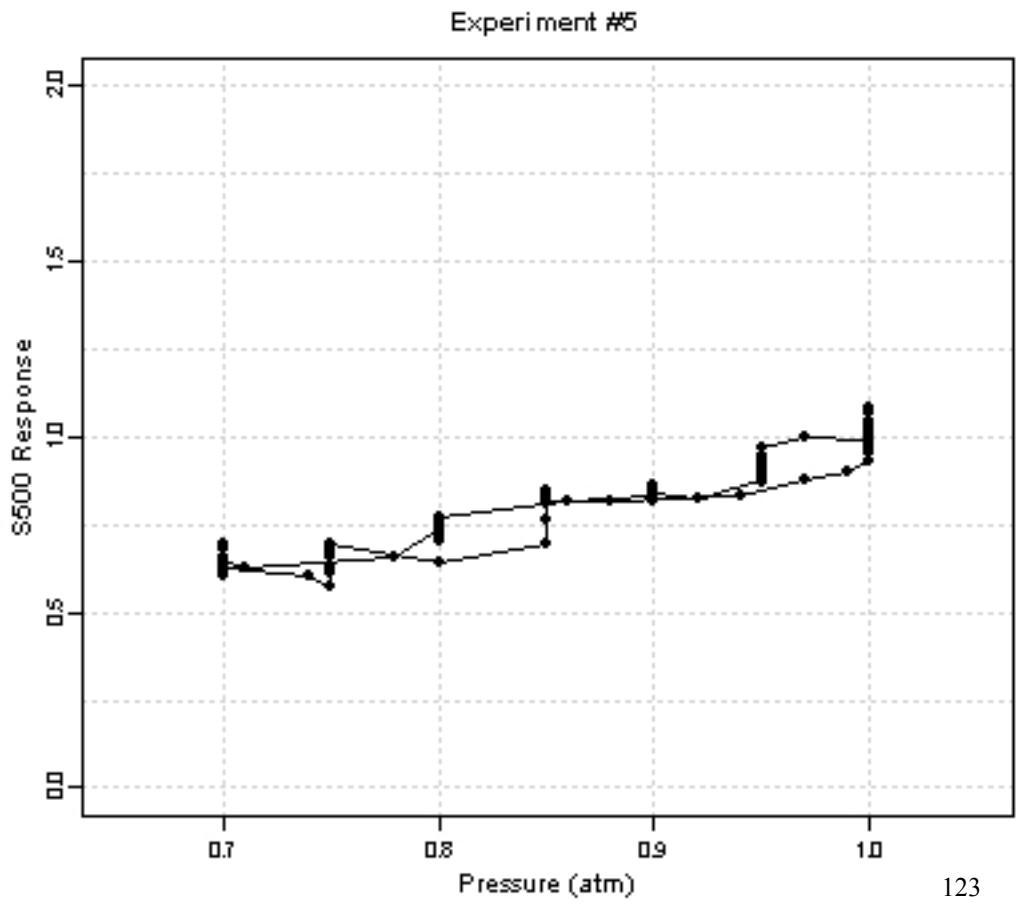
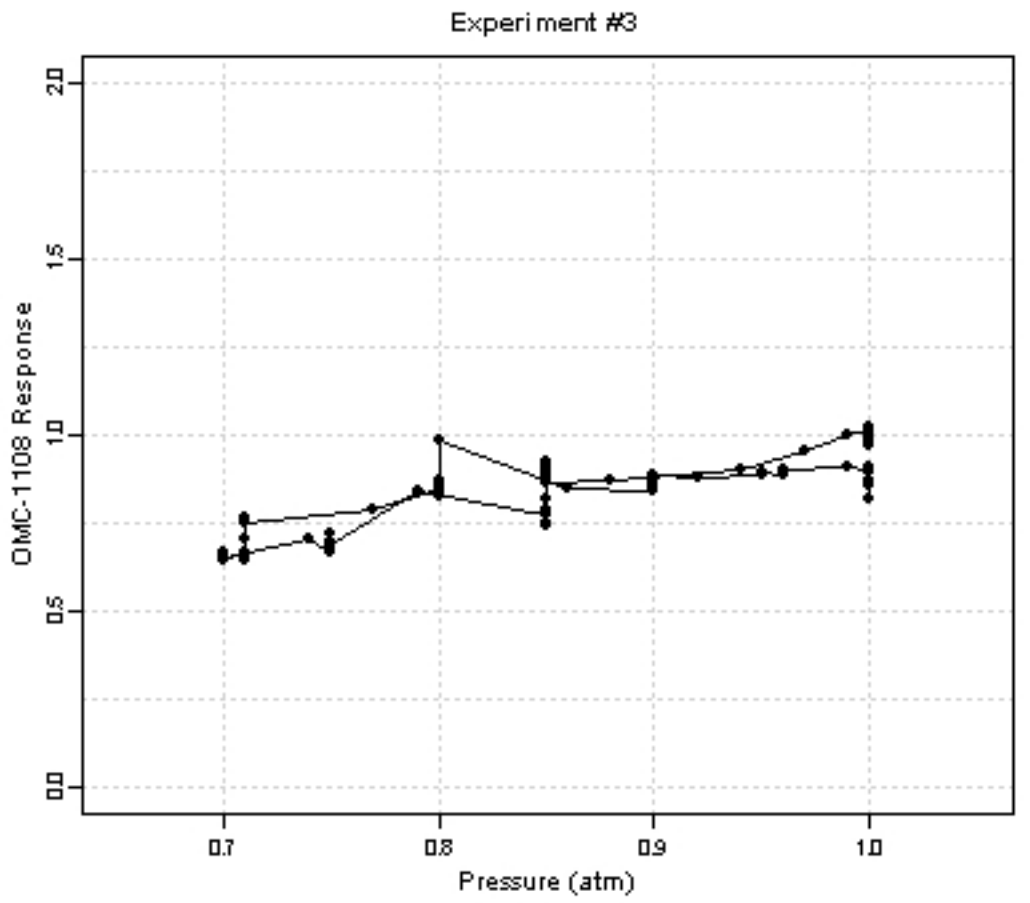
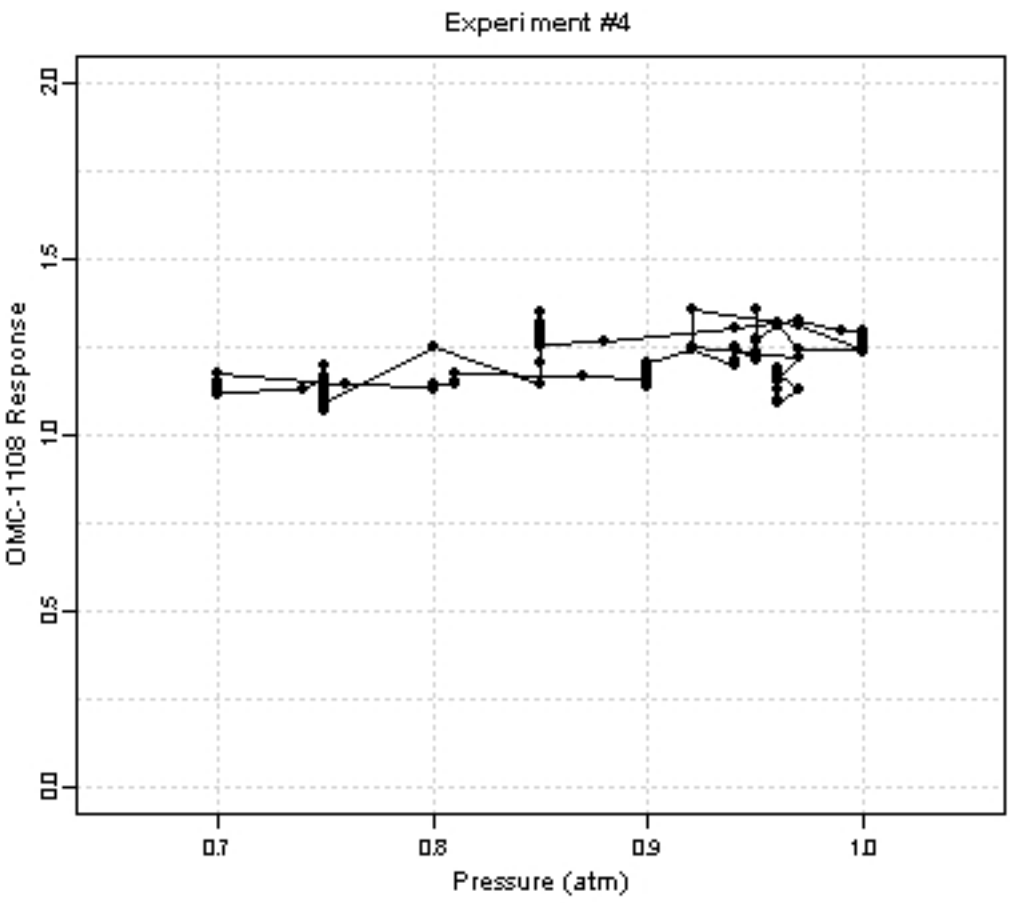


Fig. D4 Ozone Tests: Variable Pressure: OMC-1108/API (Expts 1-5)





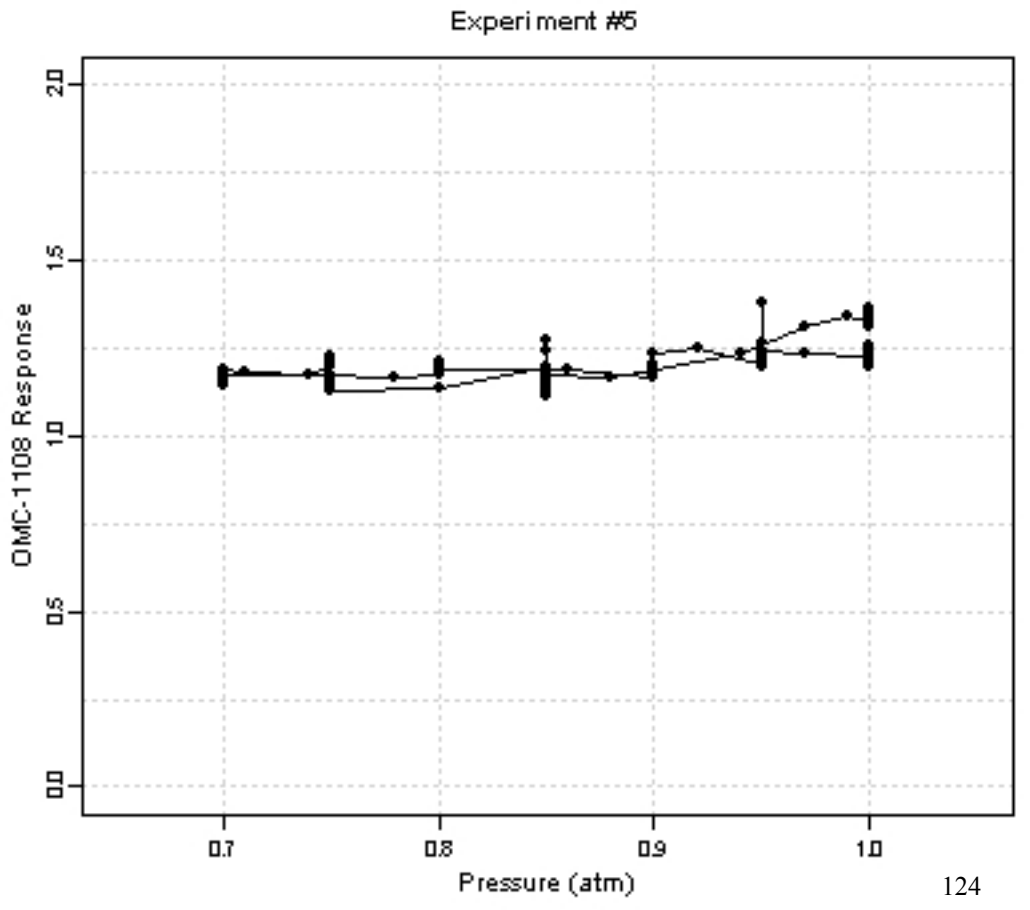
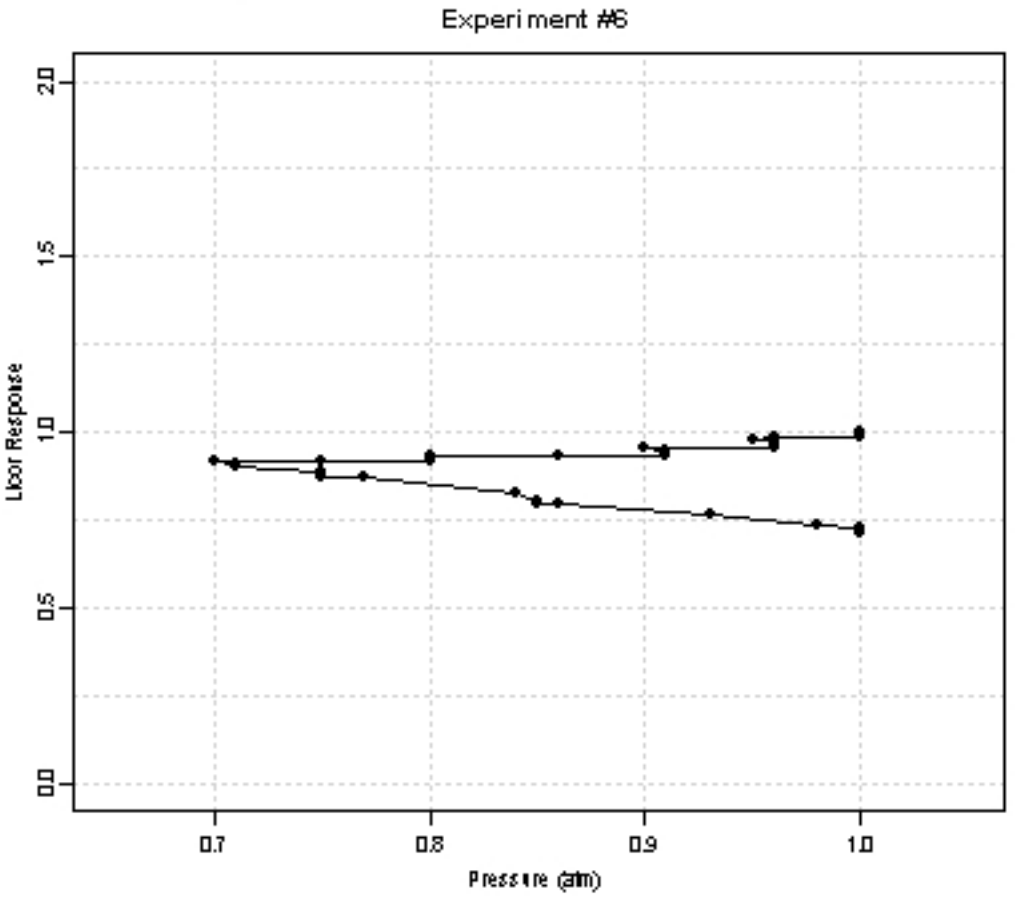
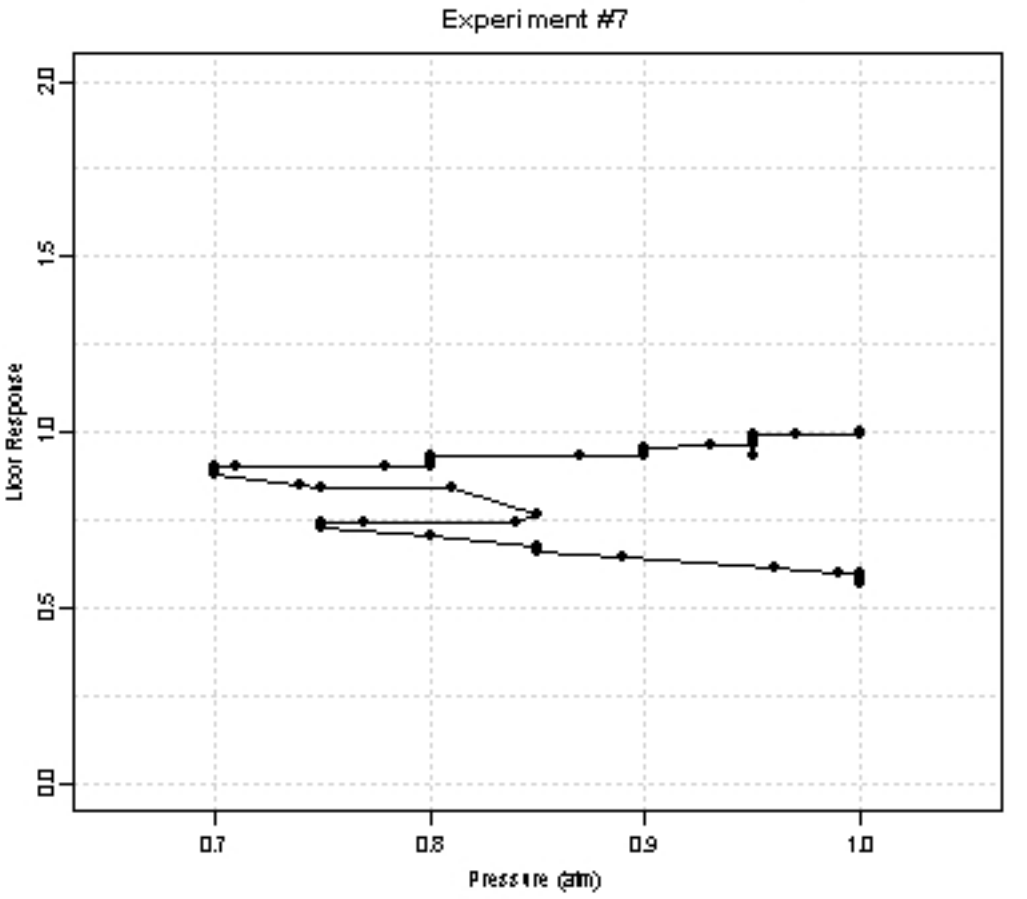
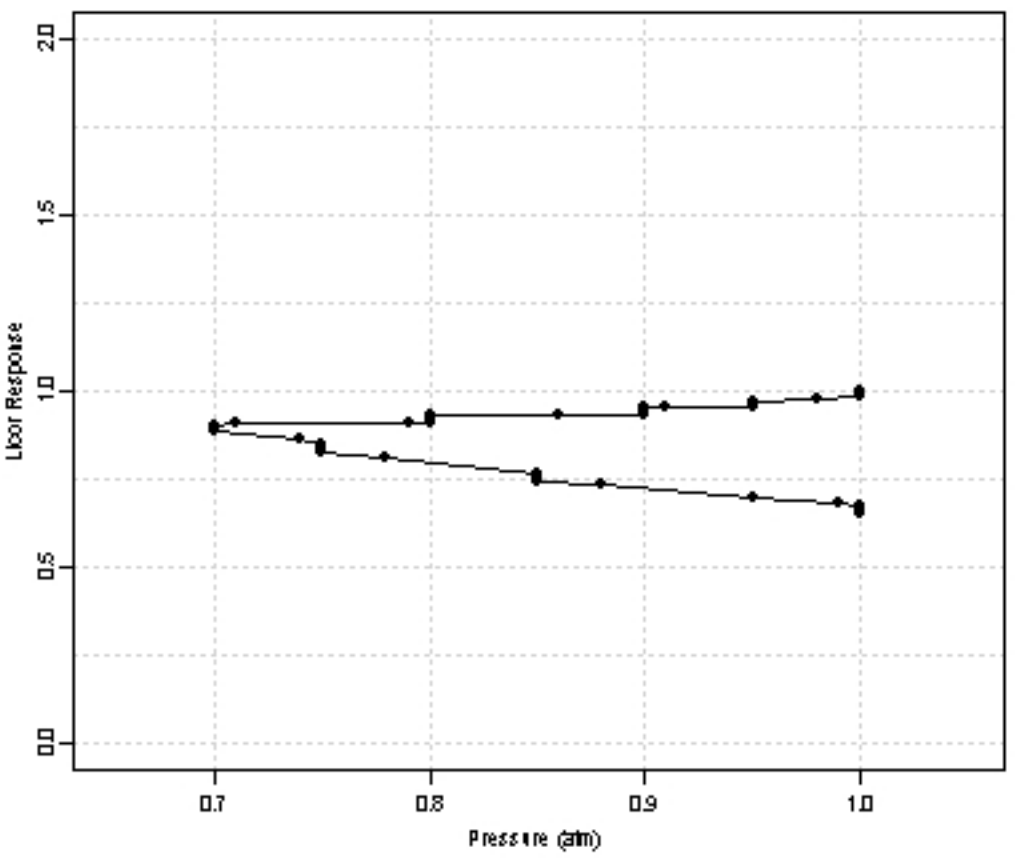


Fig. D5 CO/CO2 Tests: Variable Pressure #2: Licor/Licor CO2 (Expts 6-9)







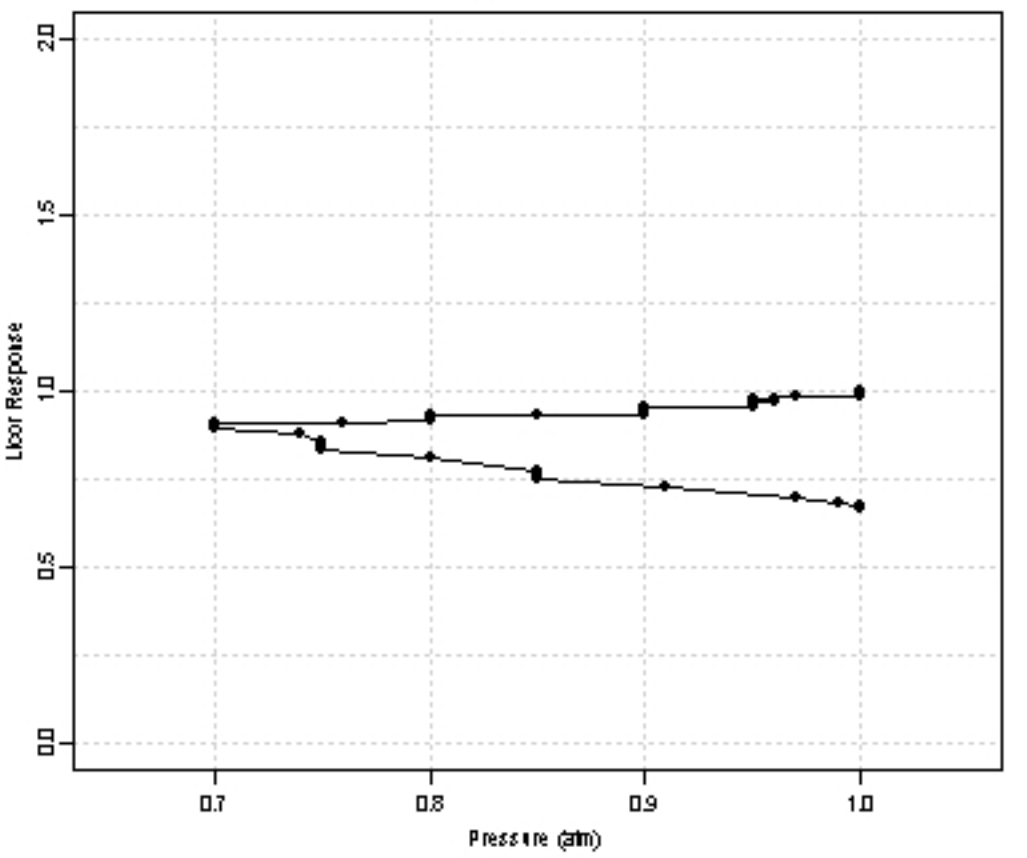
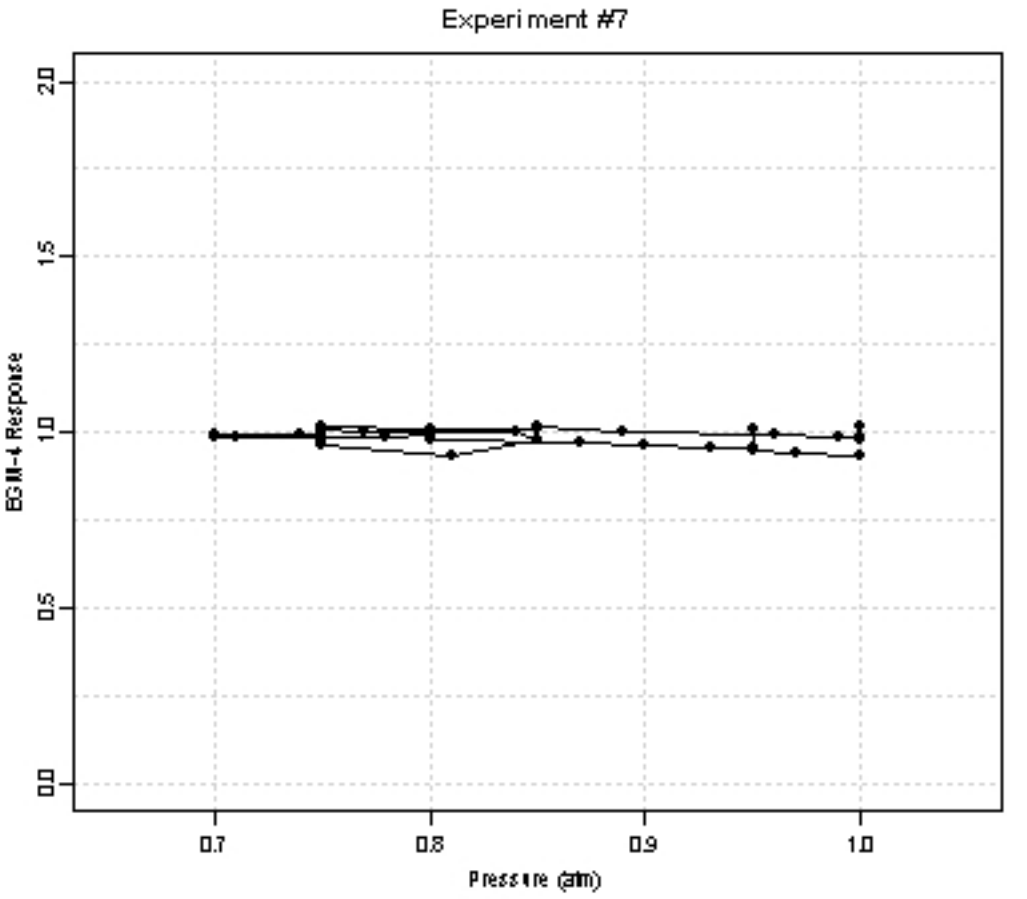
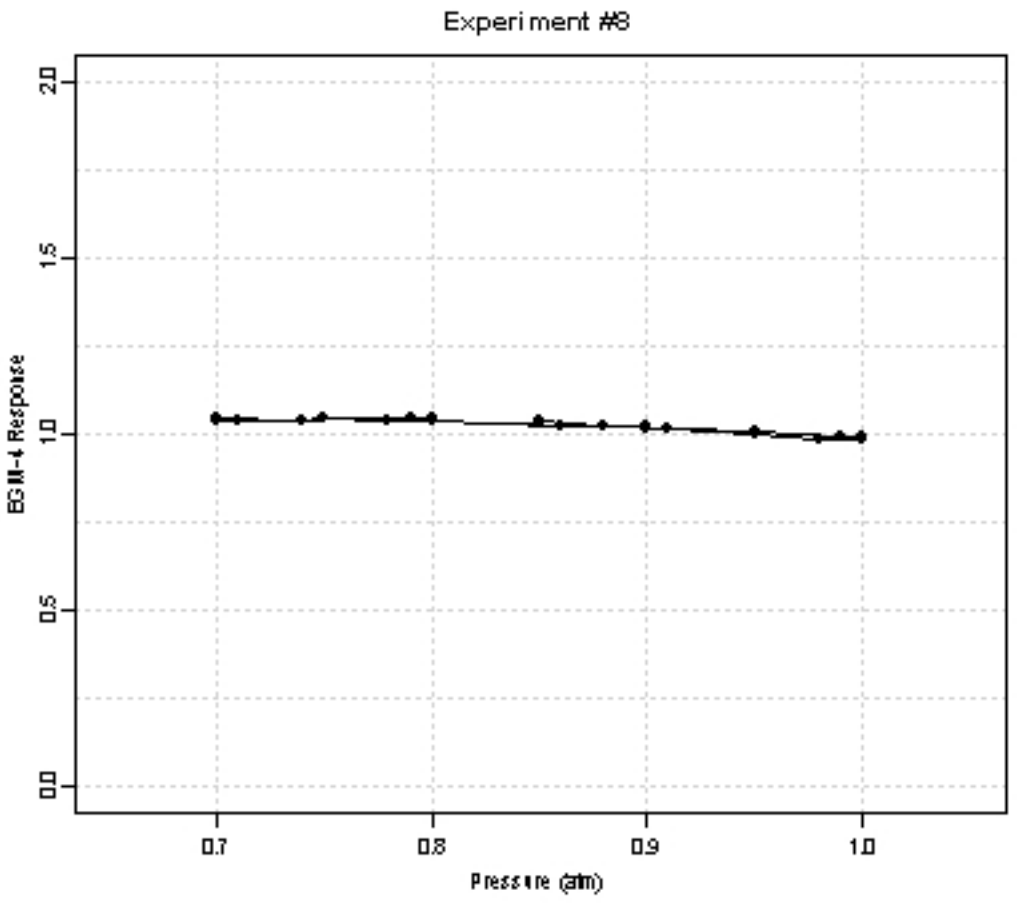


Fig. D6 CO/CO2 Tests: Variable Pressure #2: EGM-4/Licor CO2 (Expts 6-9)





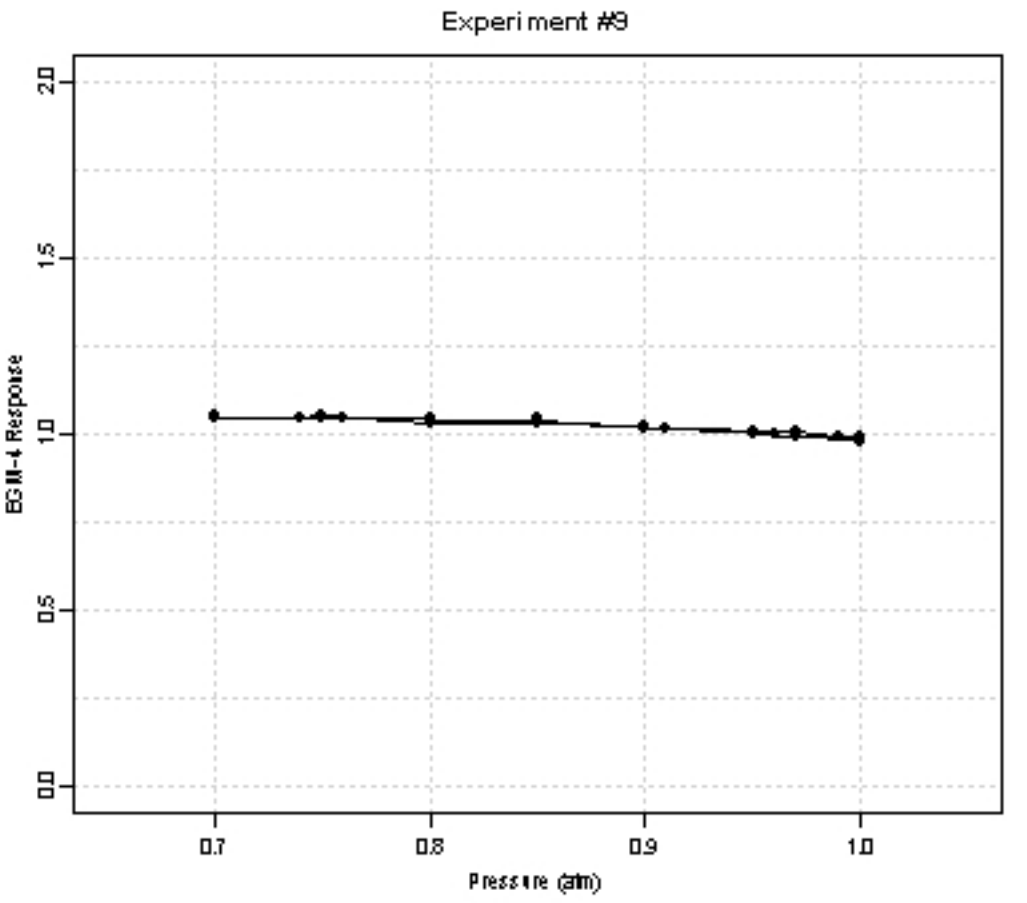
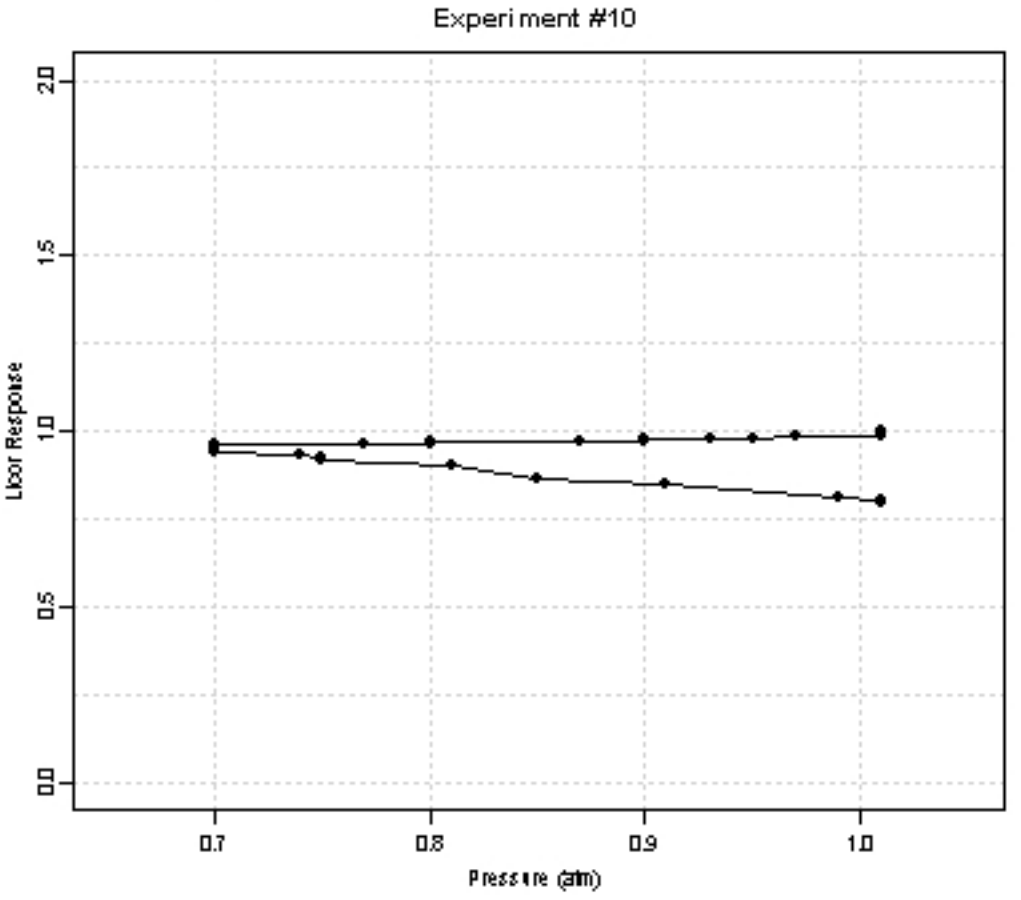
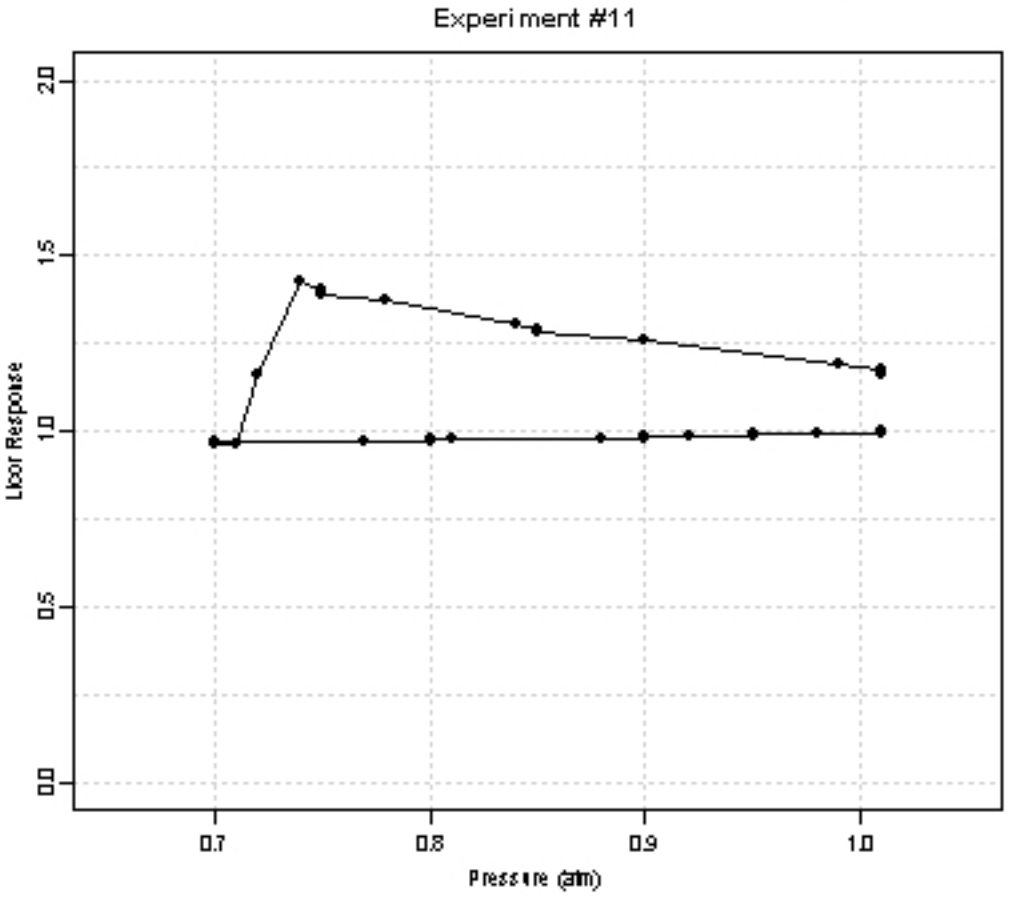
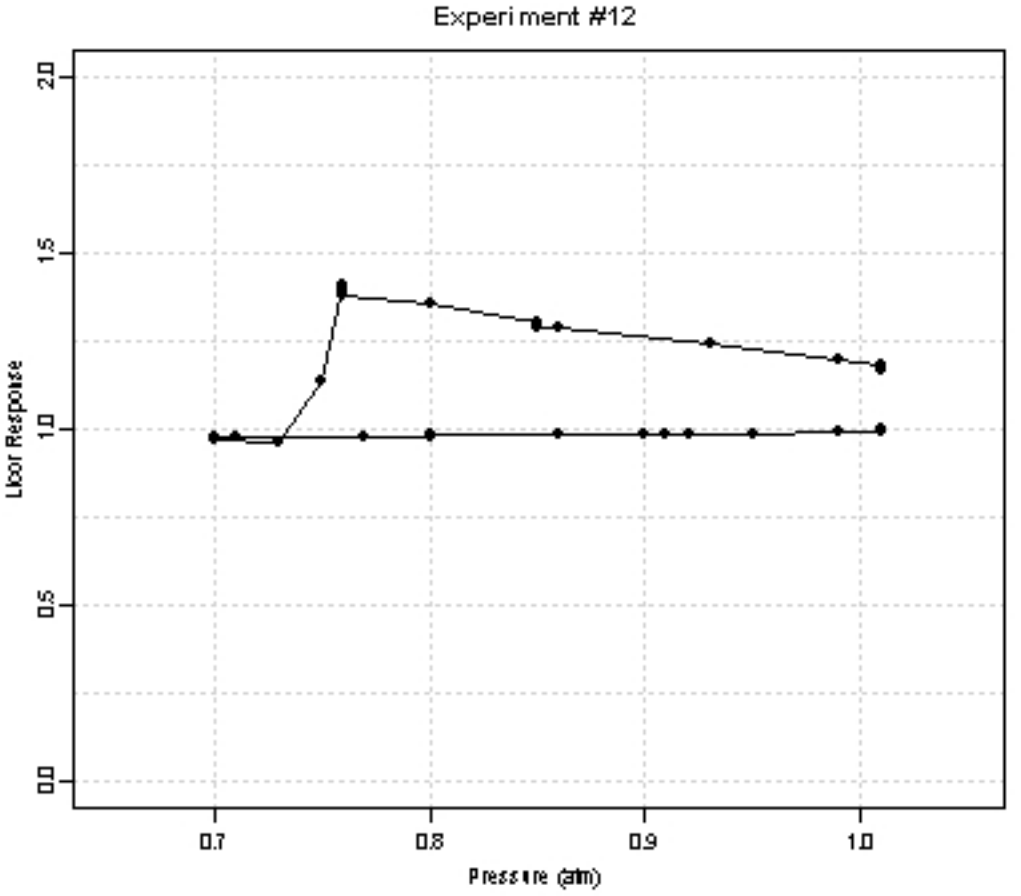
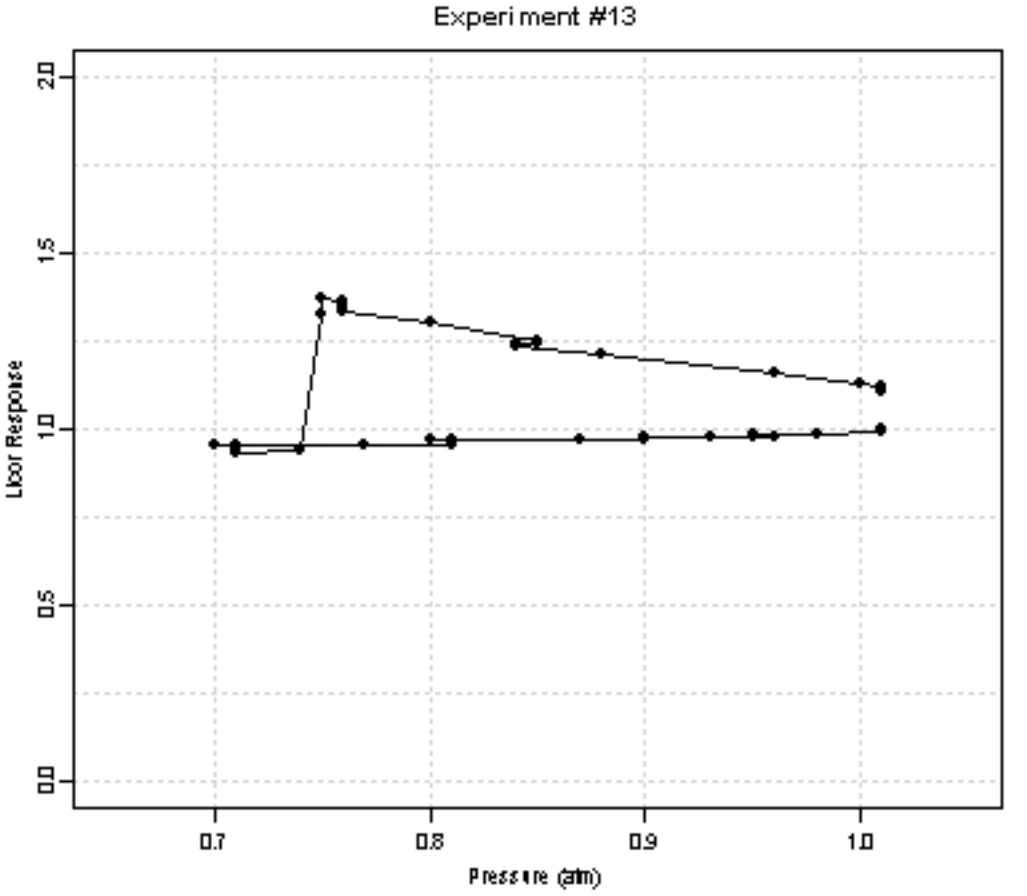


Fig. D7 CO/CO2 Tests: Variable Pressure #1: Licor/Licor CO2 (Expts 10-14)









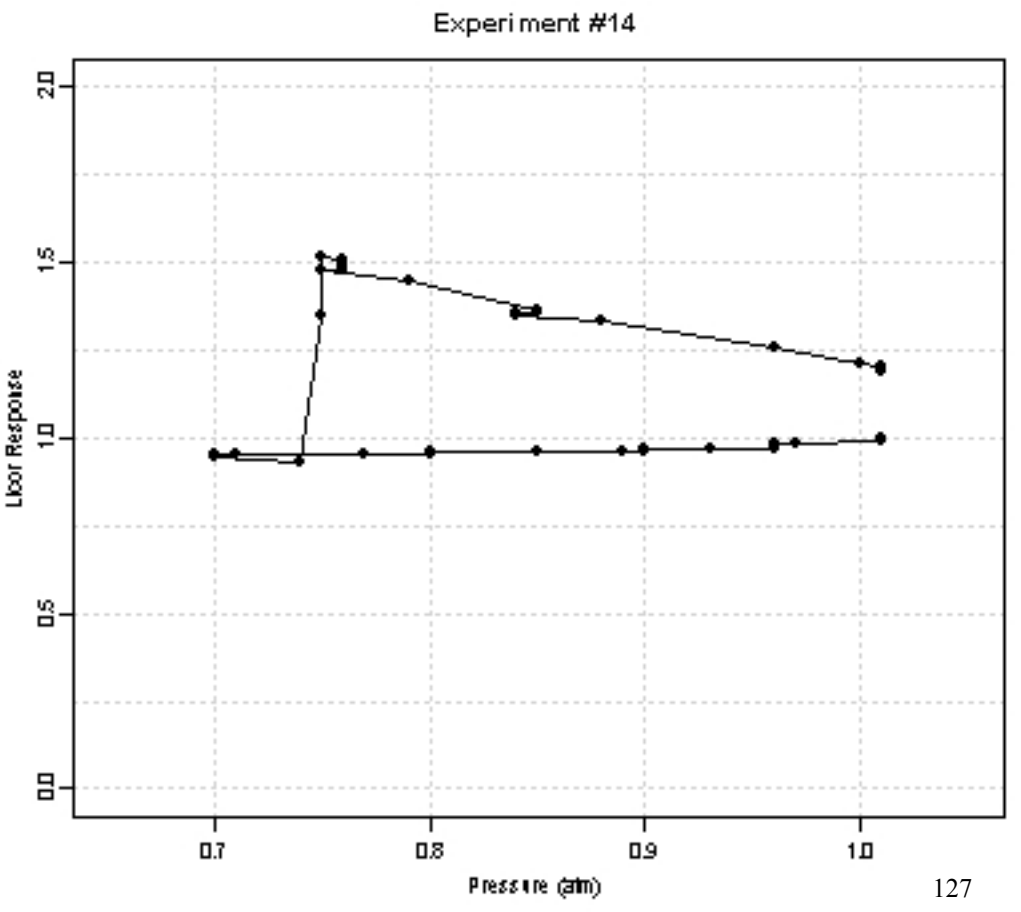
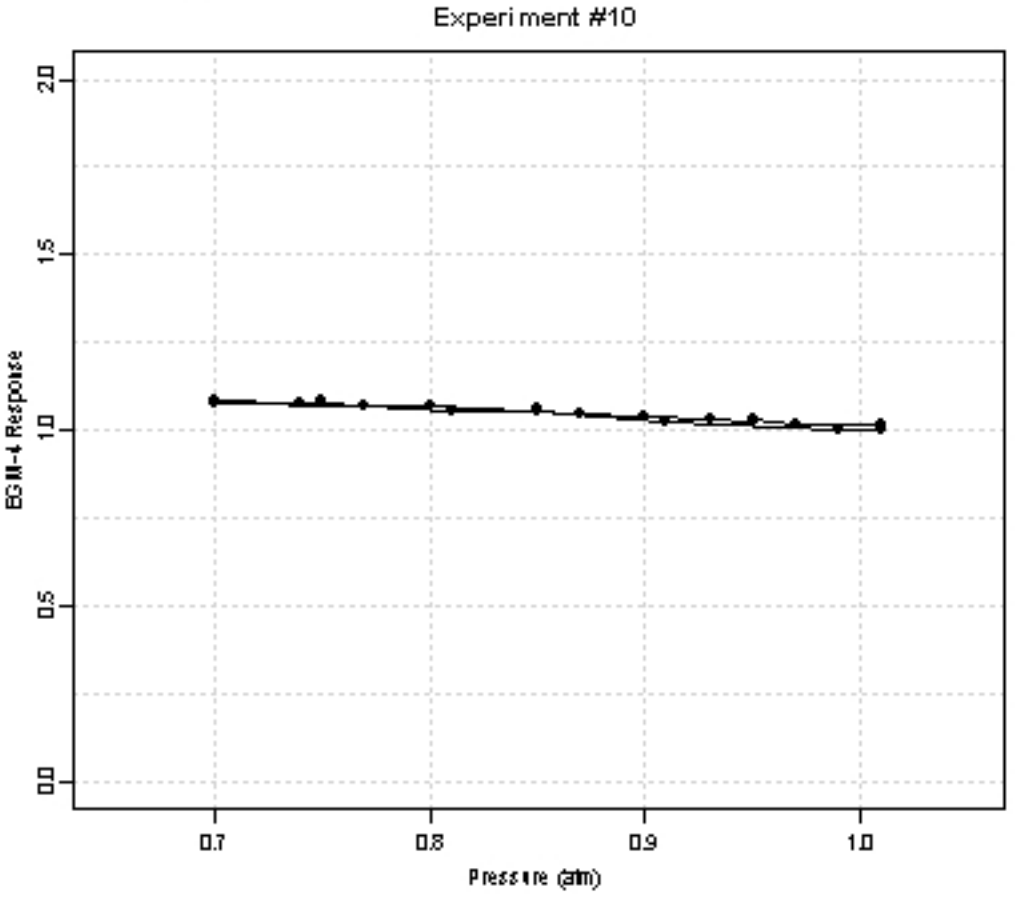
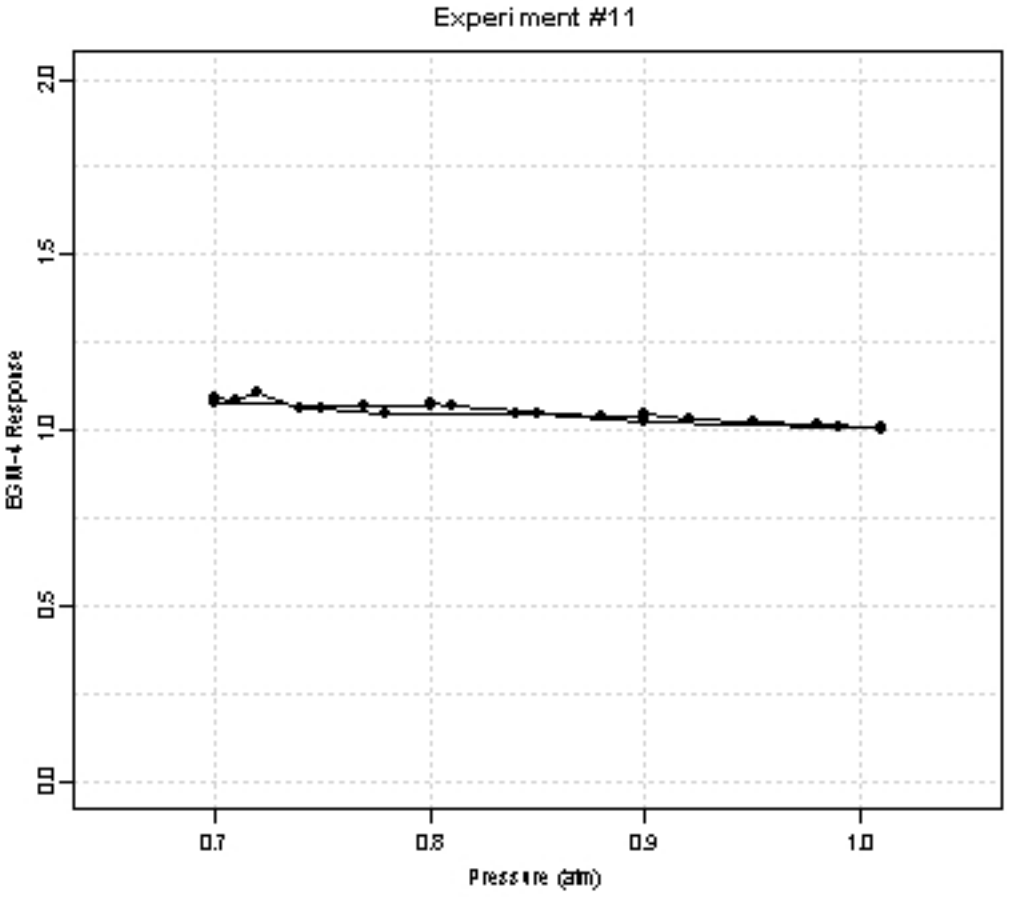
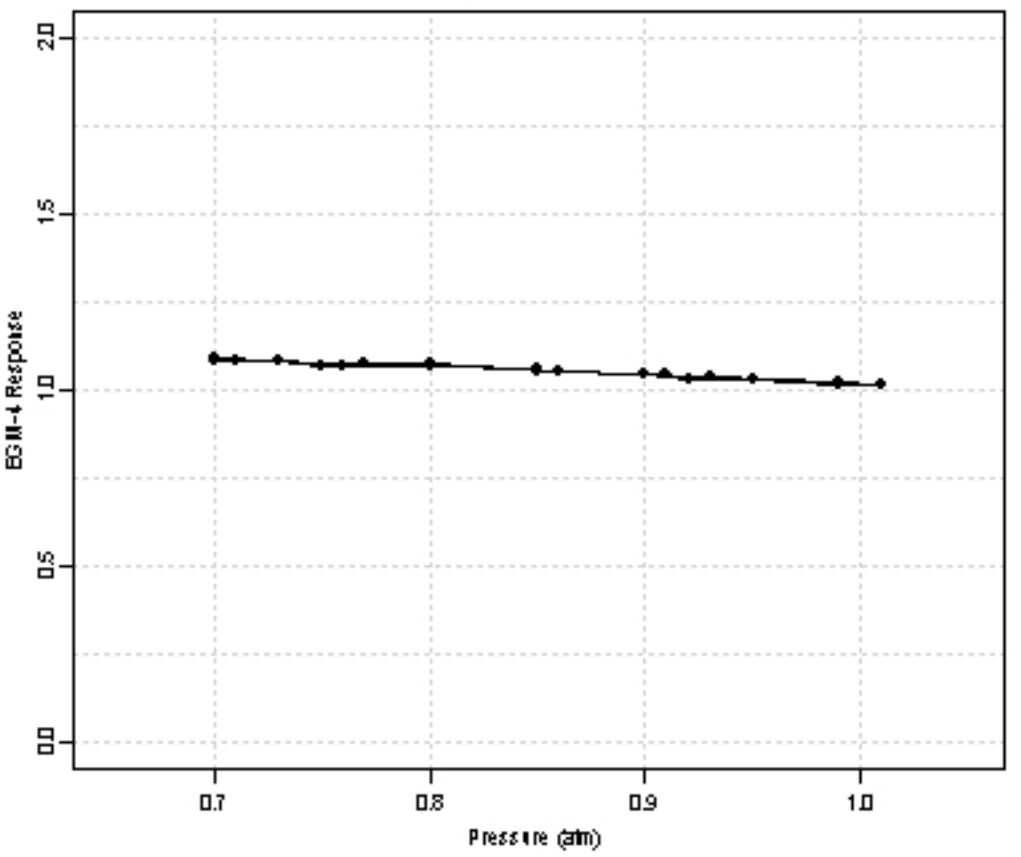


Fig. D8 CO/CO2 Tests: Variable Pressure #1: EGM-4/Licor CO2 (Expts 10-14)







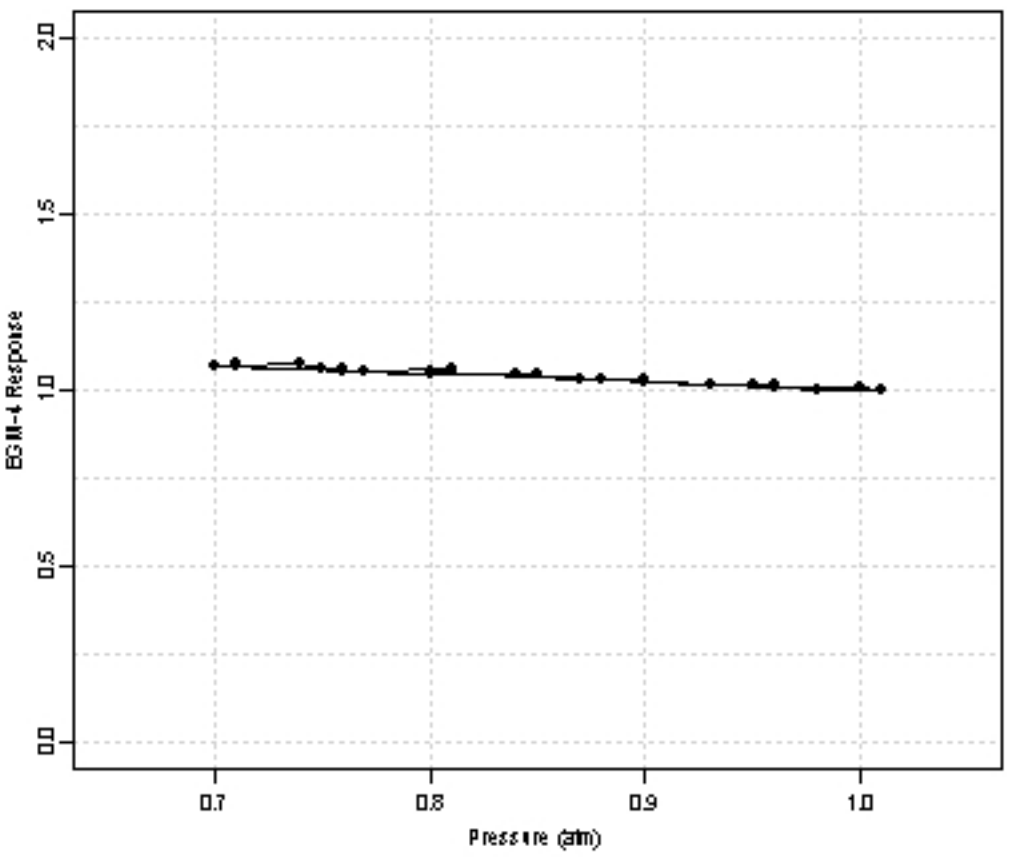
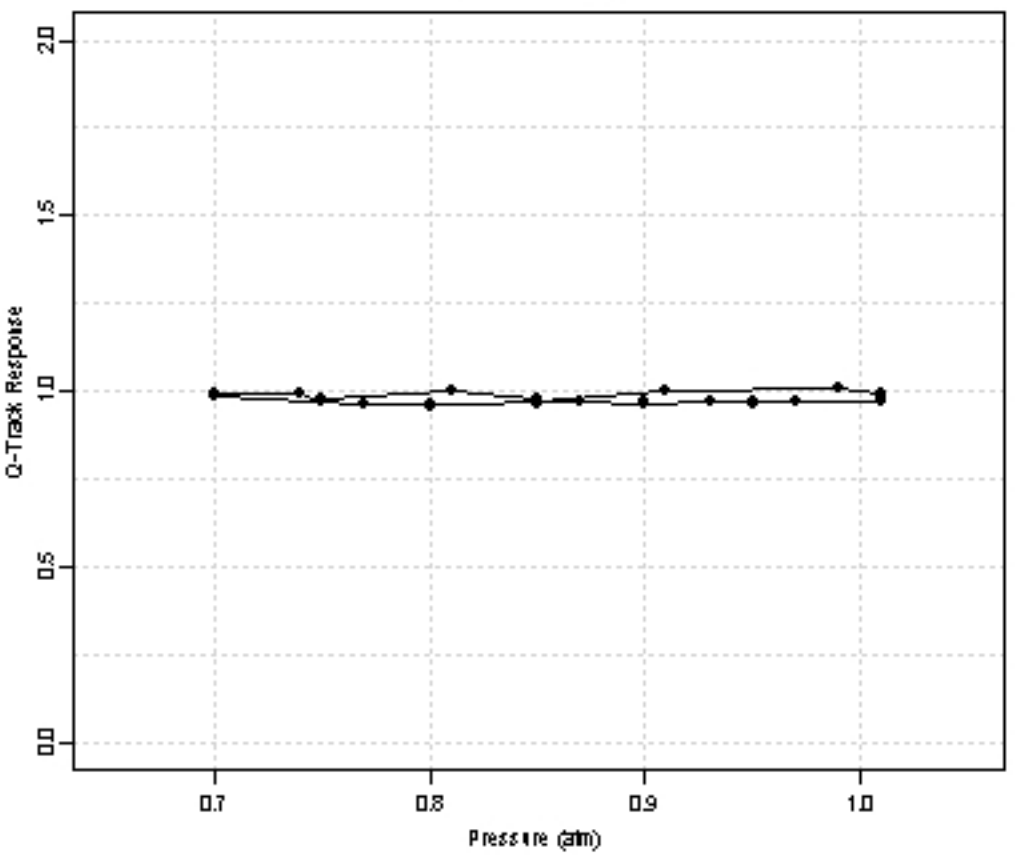
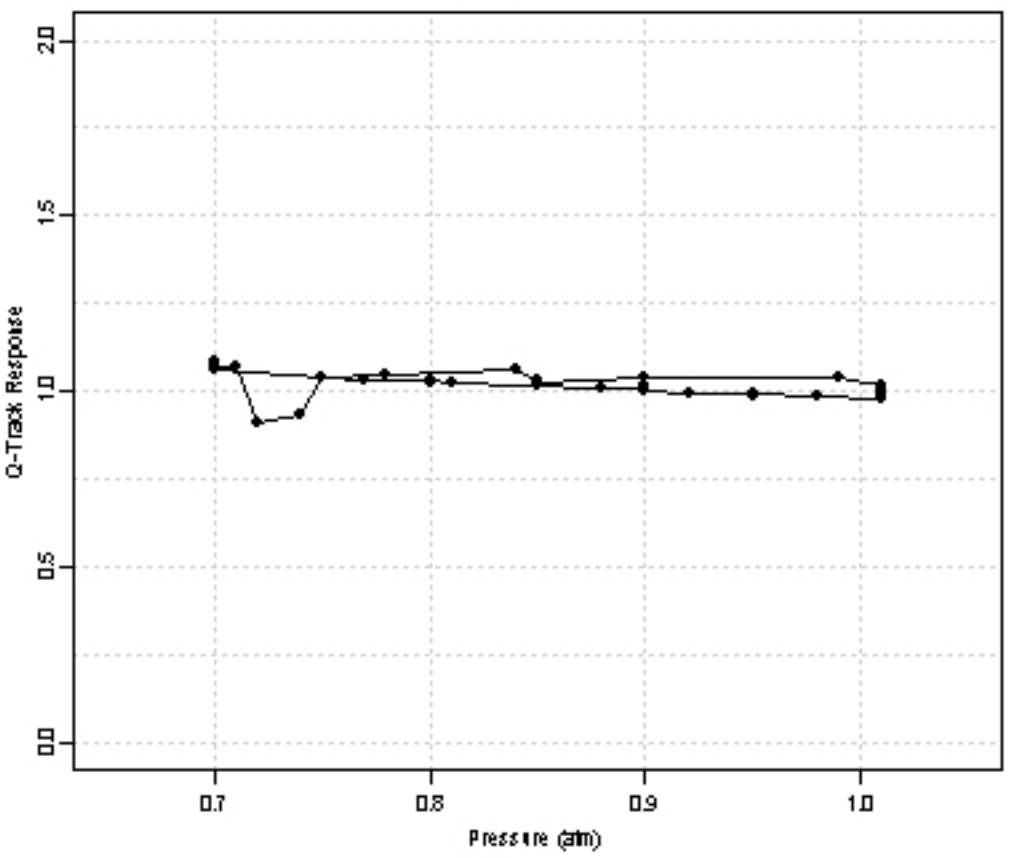
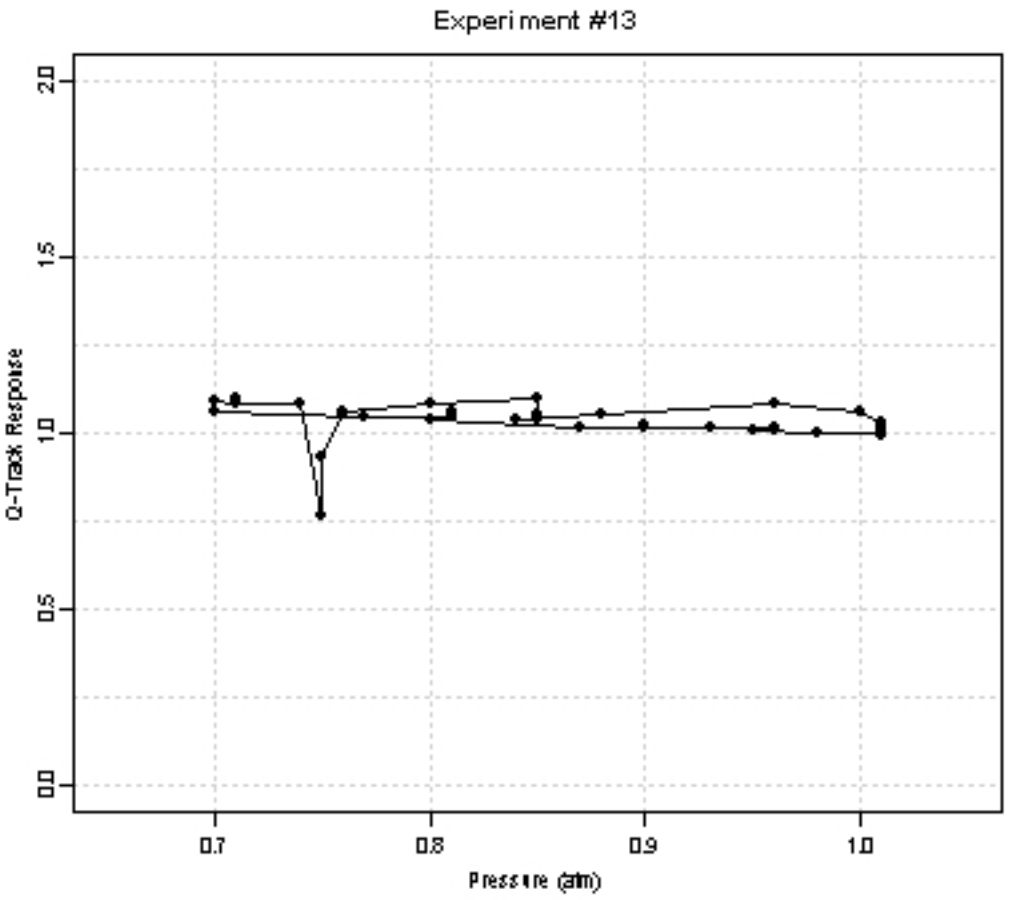


Fig. D9 CO/CO2 Tests: Variable Pressure #1: Q-Track/Licor CO2 (Expts 10-14)







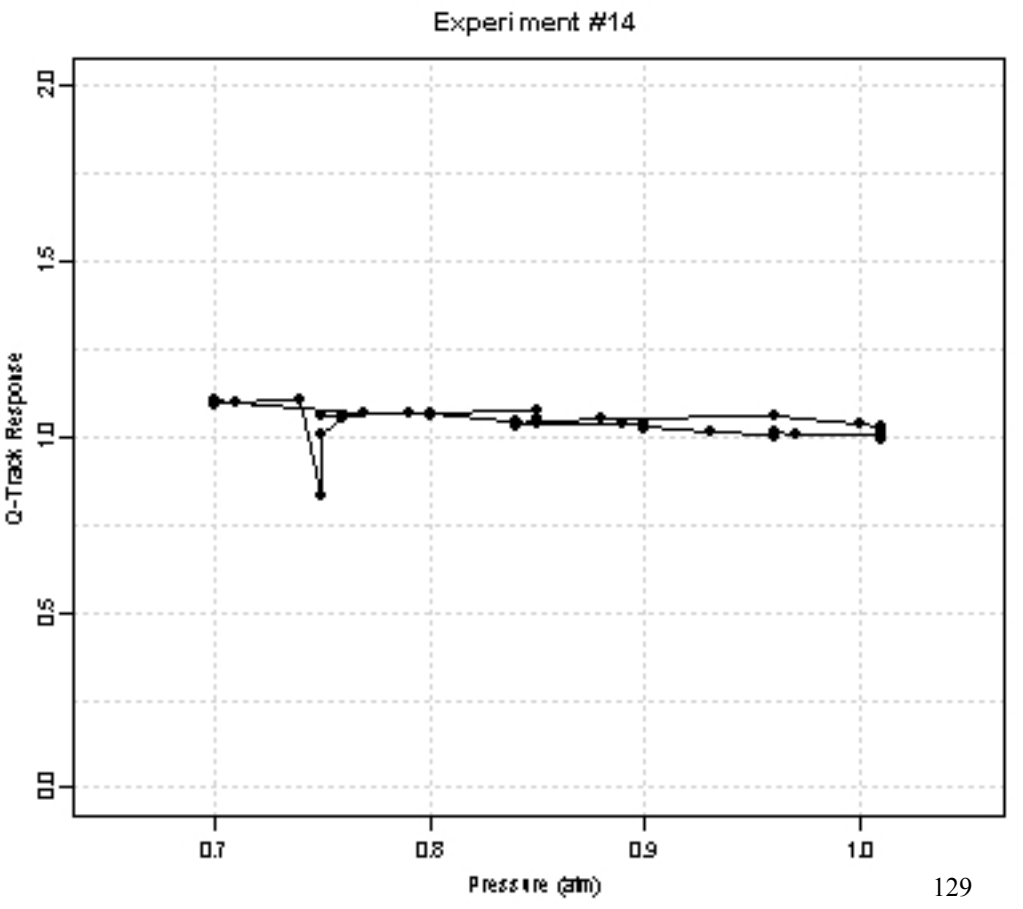
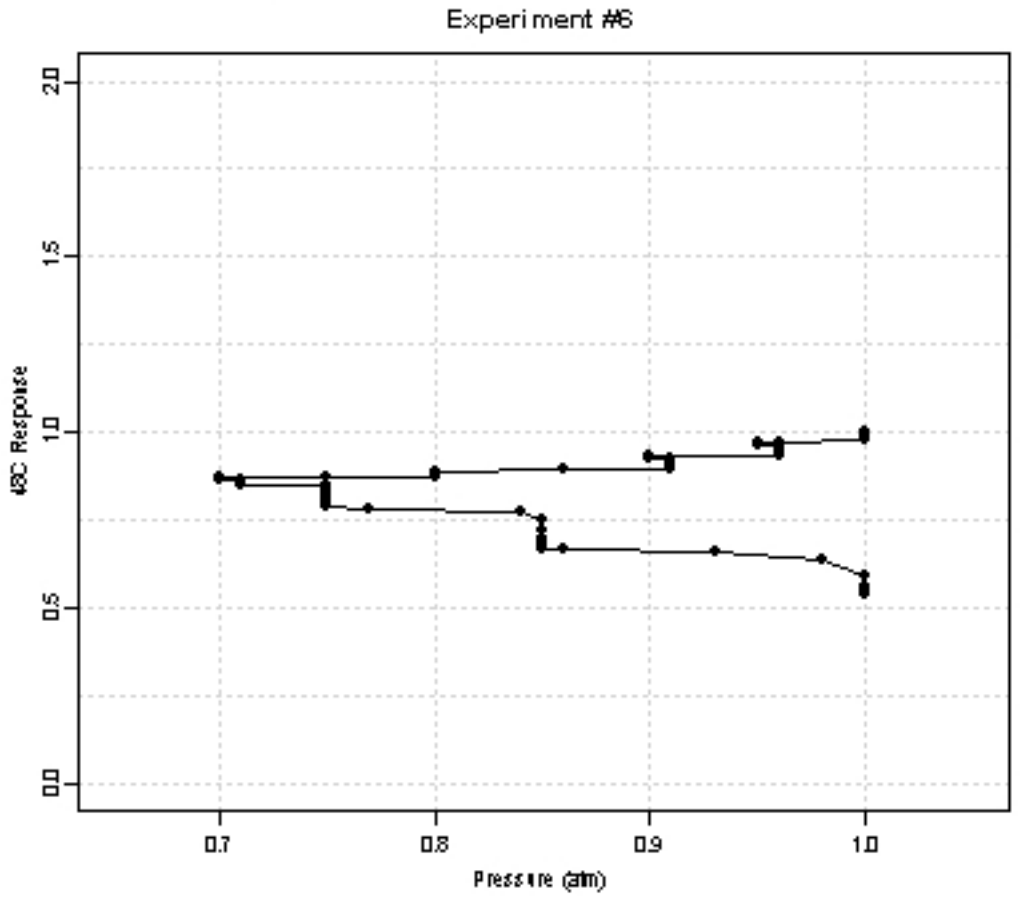
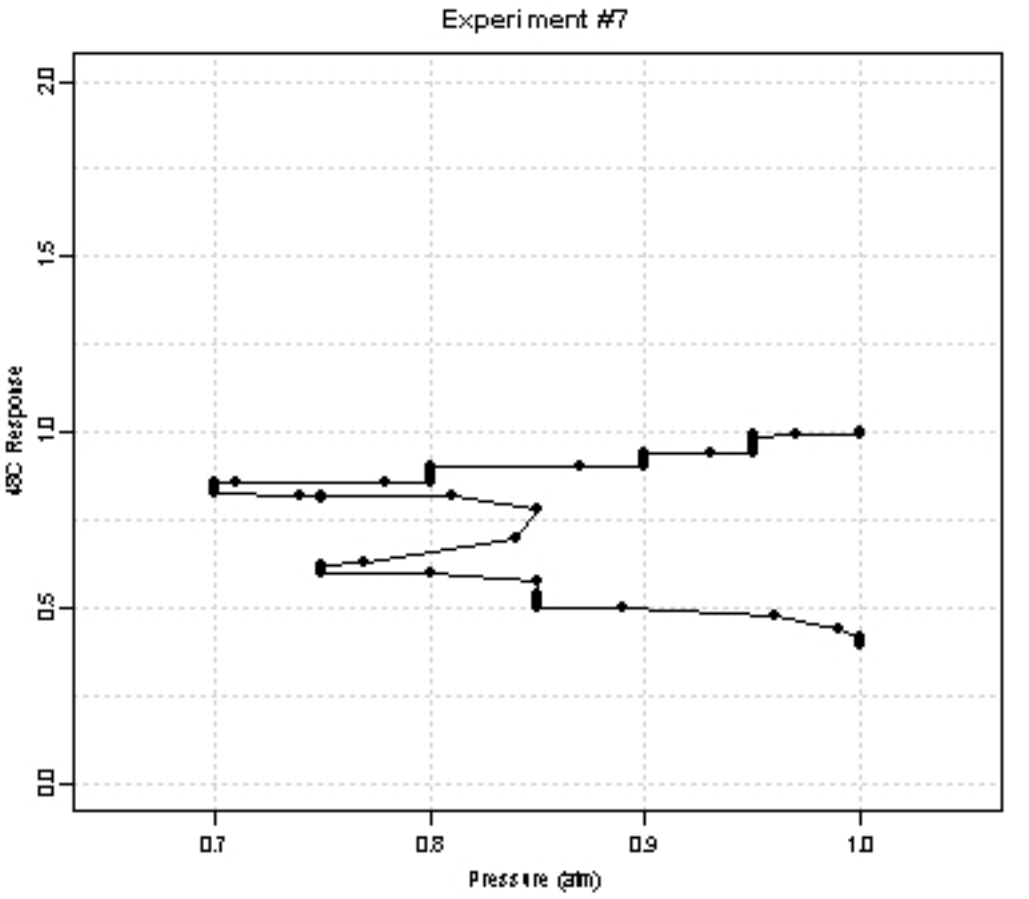
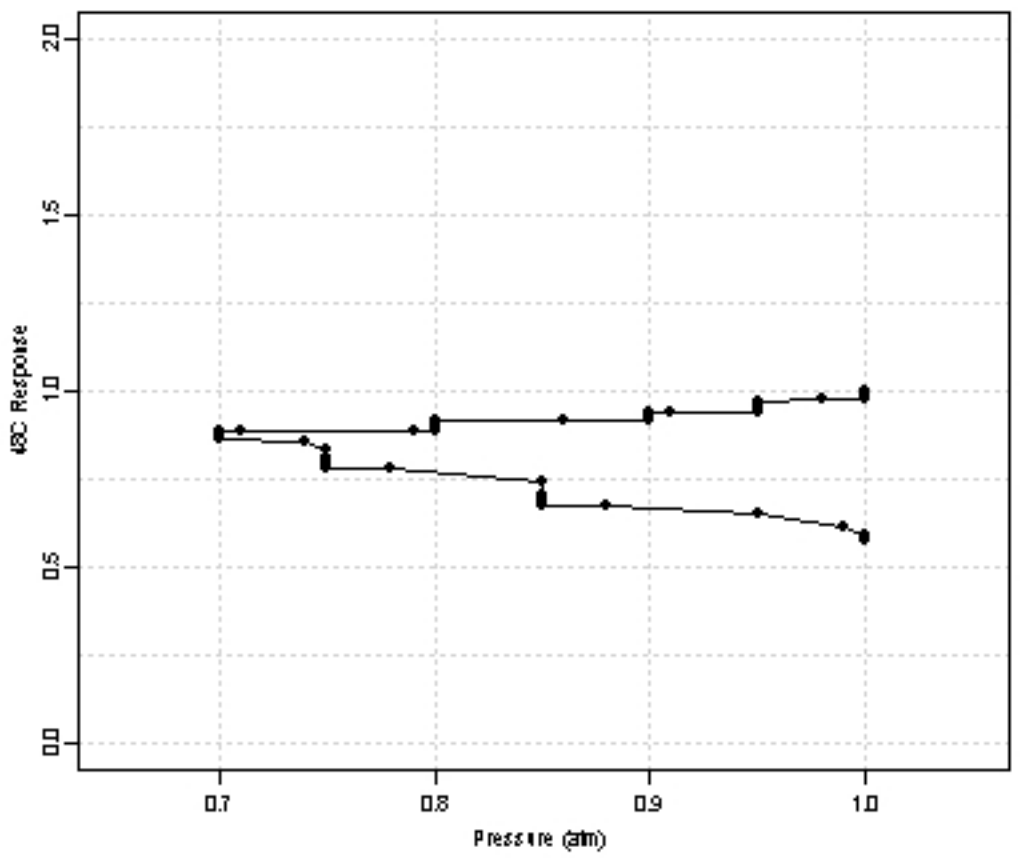


Fig. D10 CO/CO2 Tests: Variable Pressure #2: 48C/48C CO (Expts 6-9)







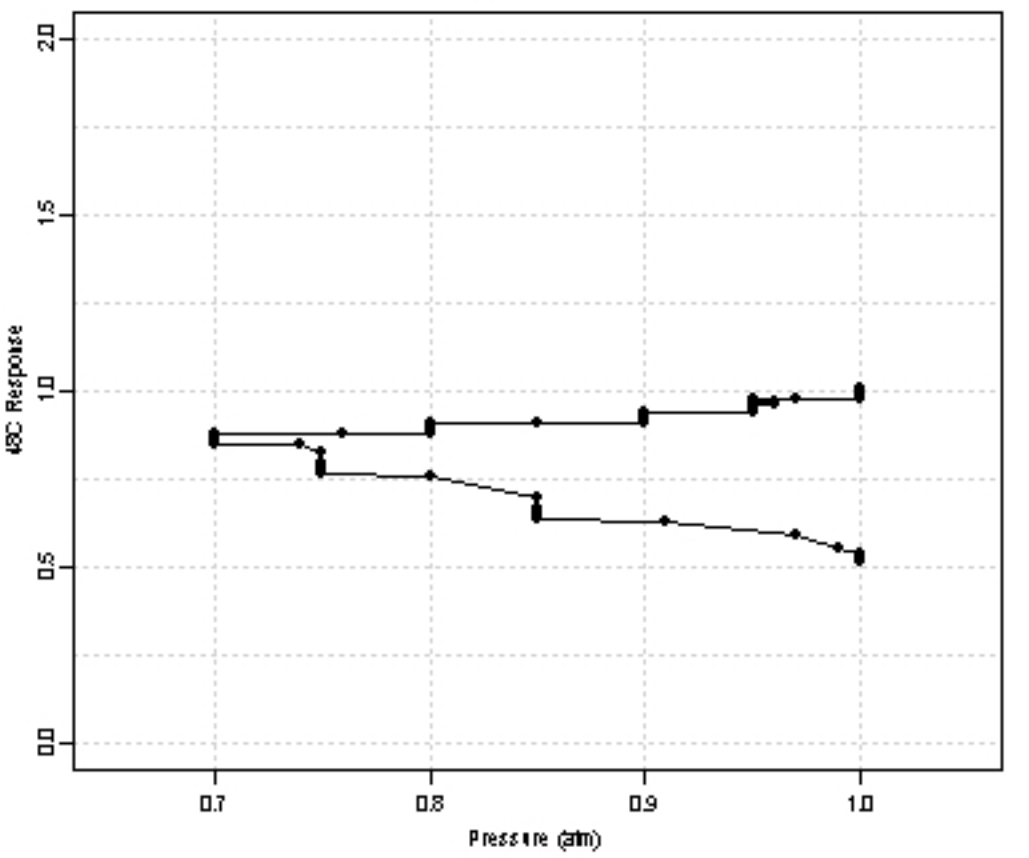
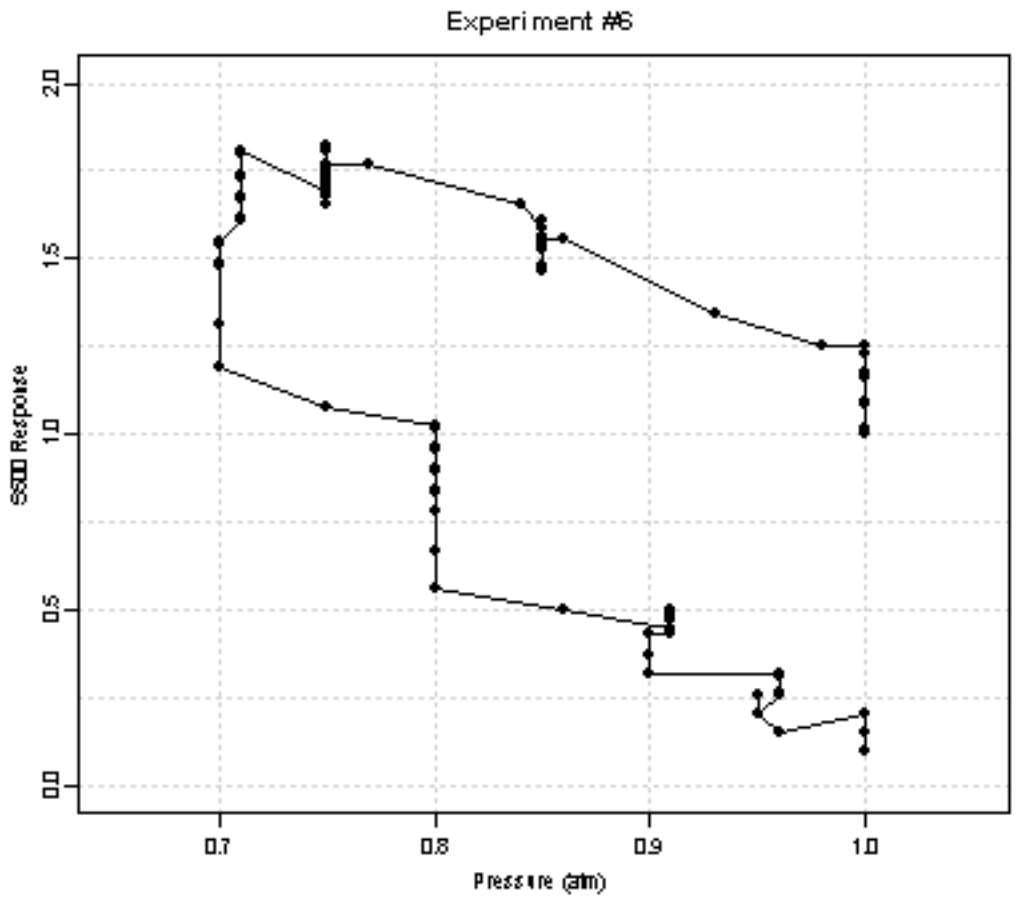
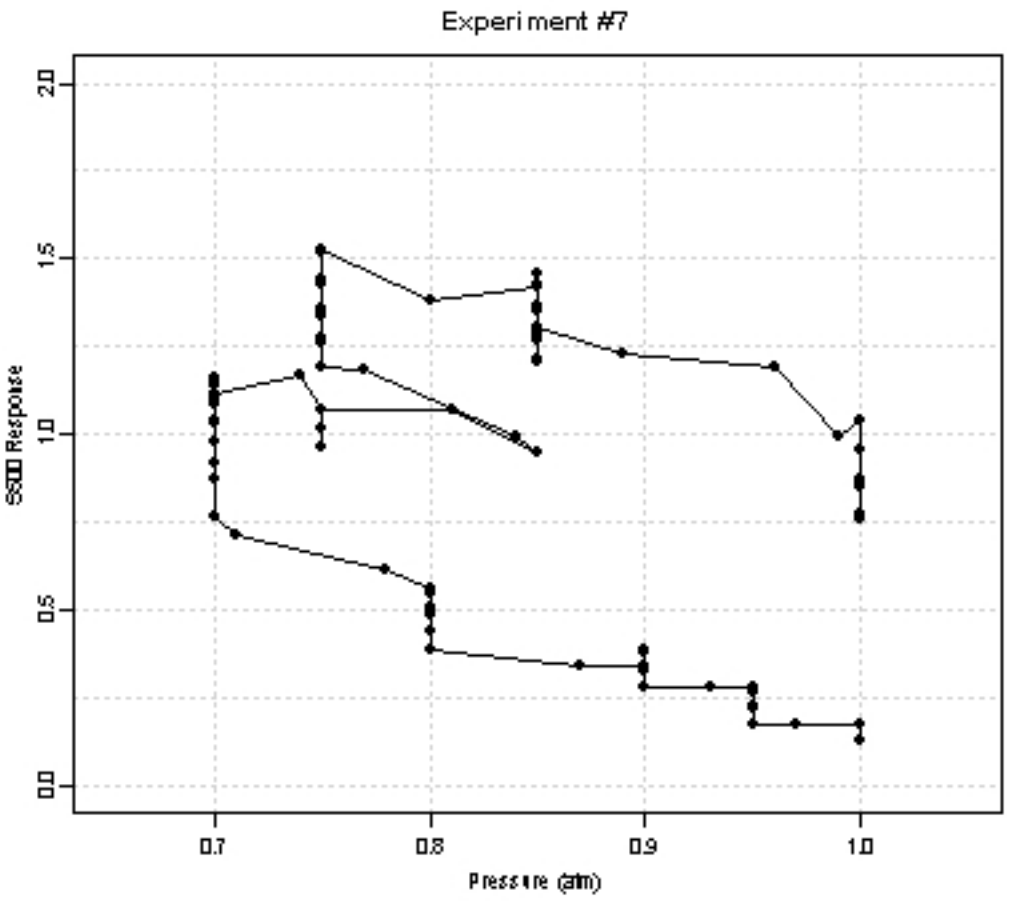
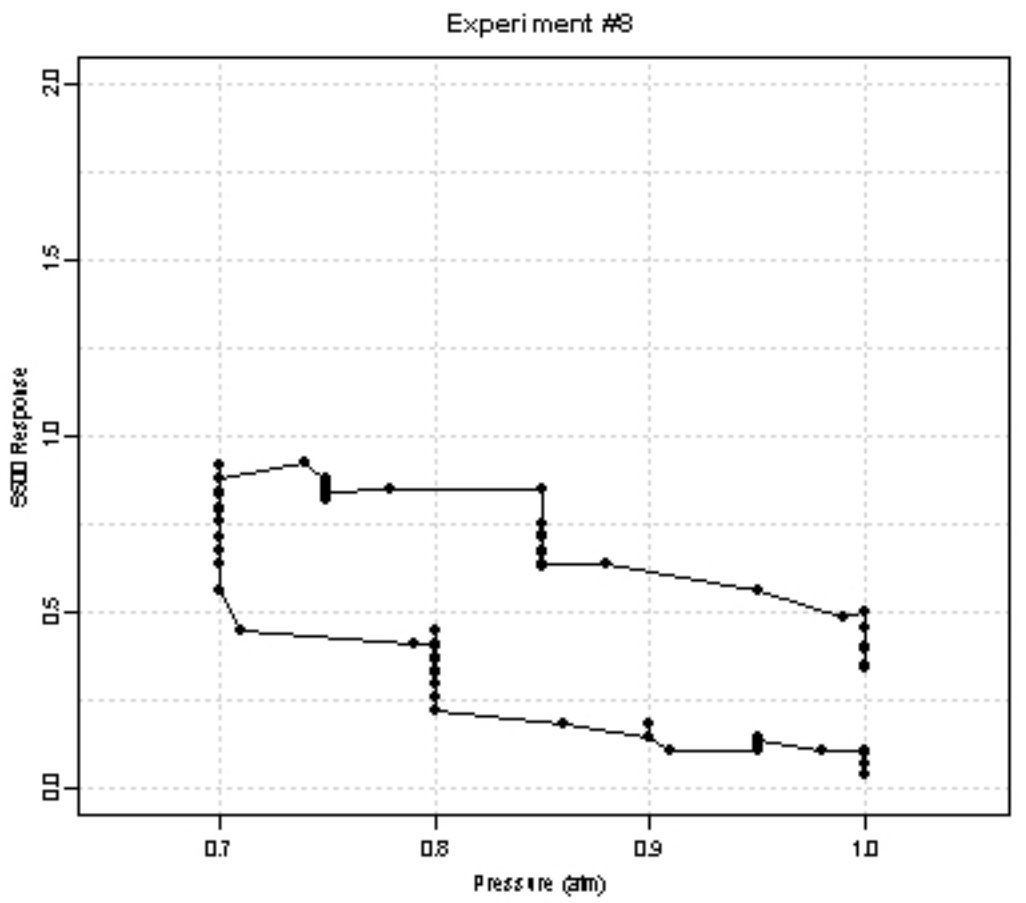


Fig. D11 CO/CO2 Tests: Variable Pressure: S500/48C CO (Expts 6-9)







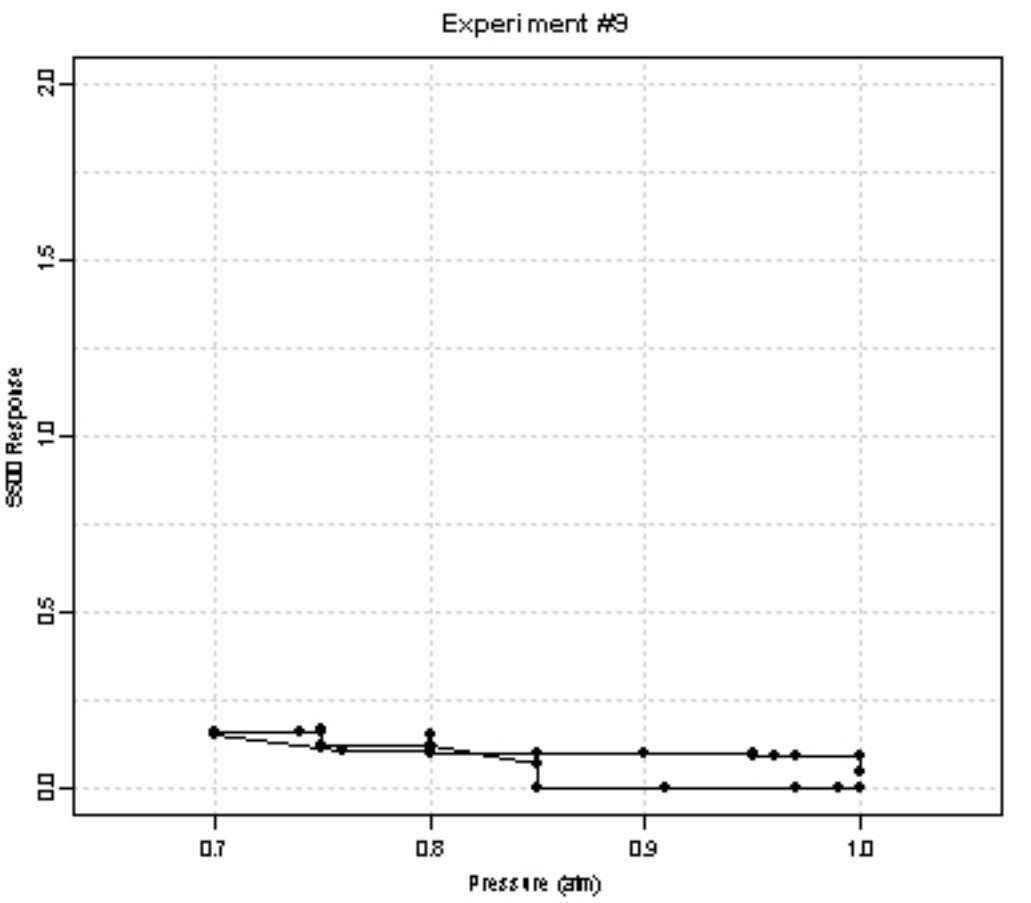
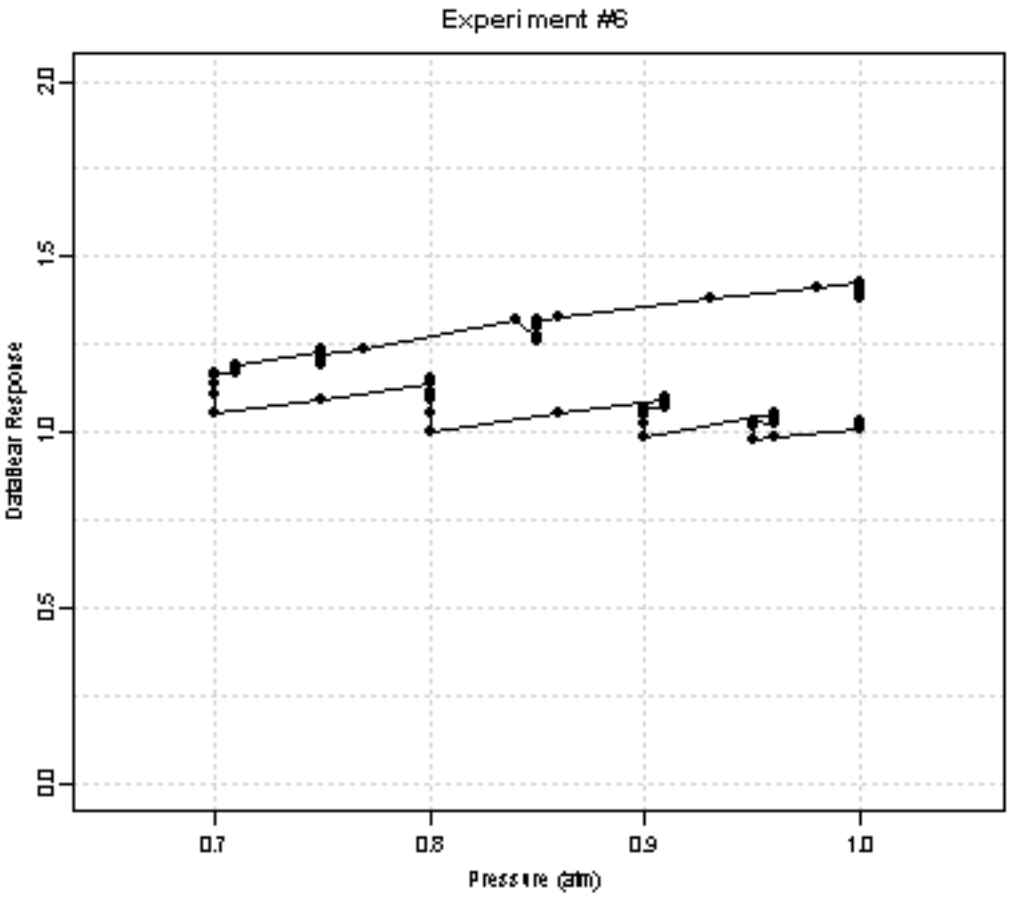
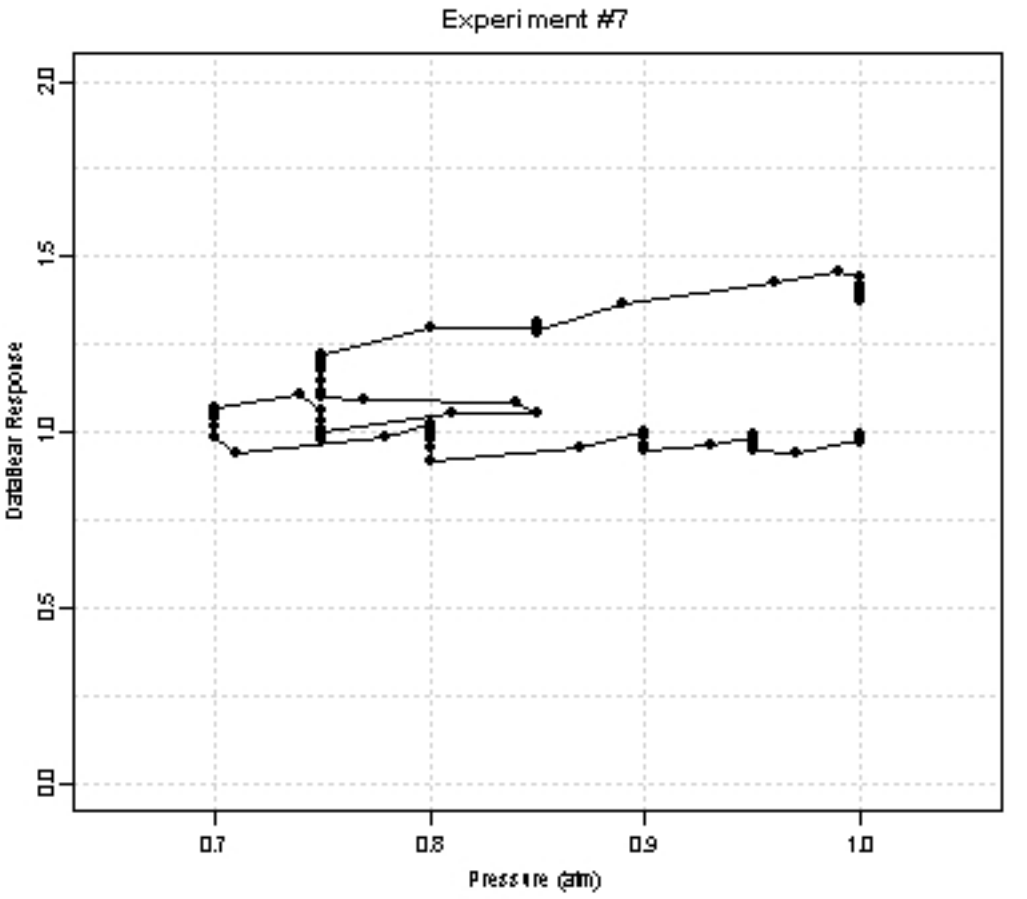
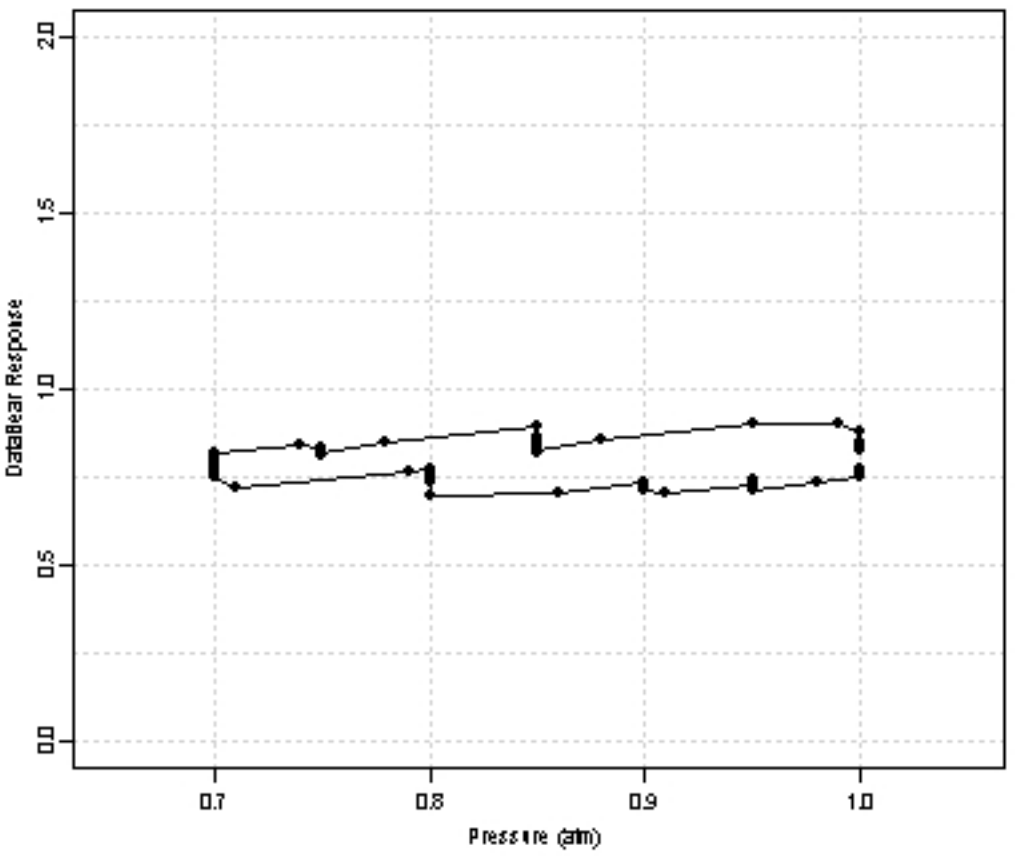


Fig. D12 CO/CO2 Tests: Variable Pressure: Databear/48C CO (Expts 6-9)







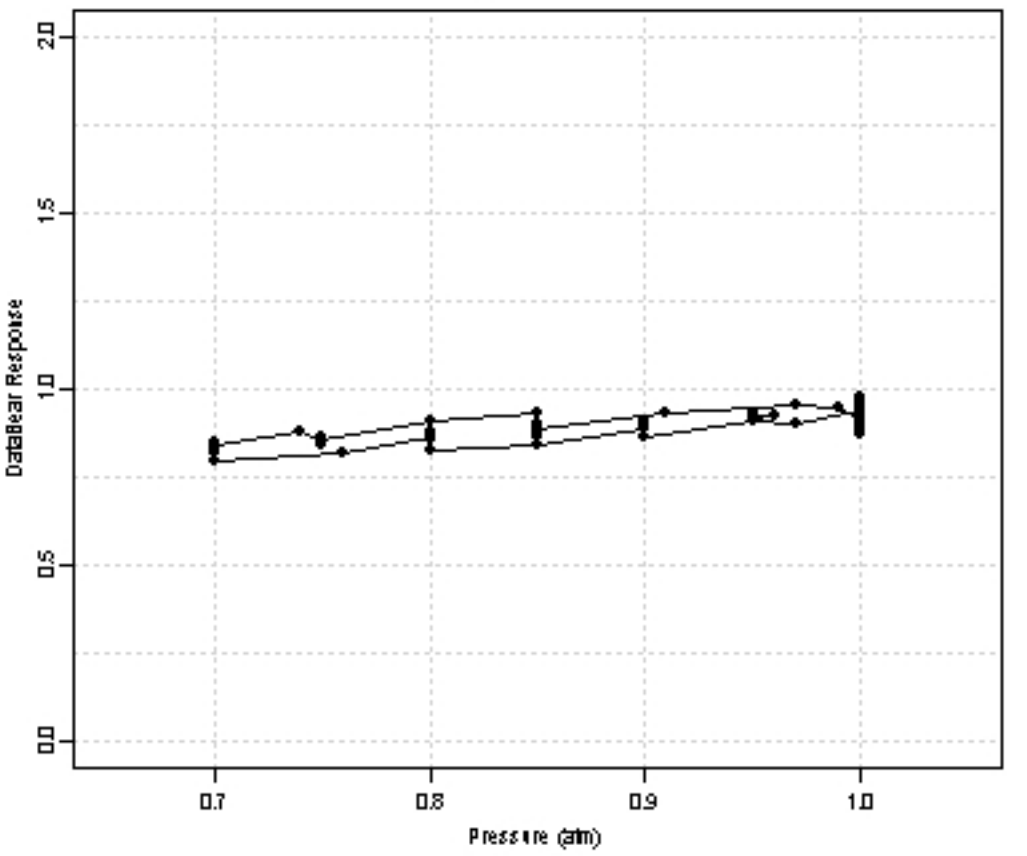
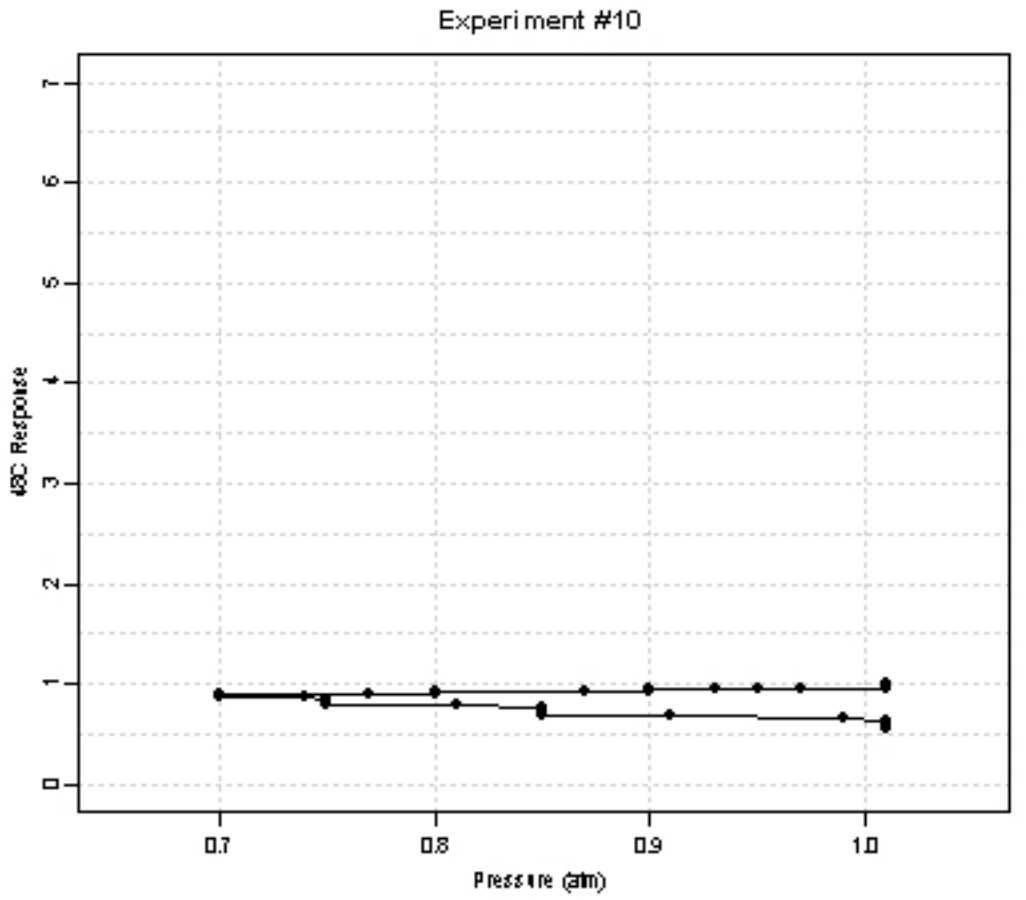
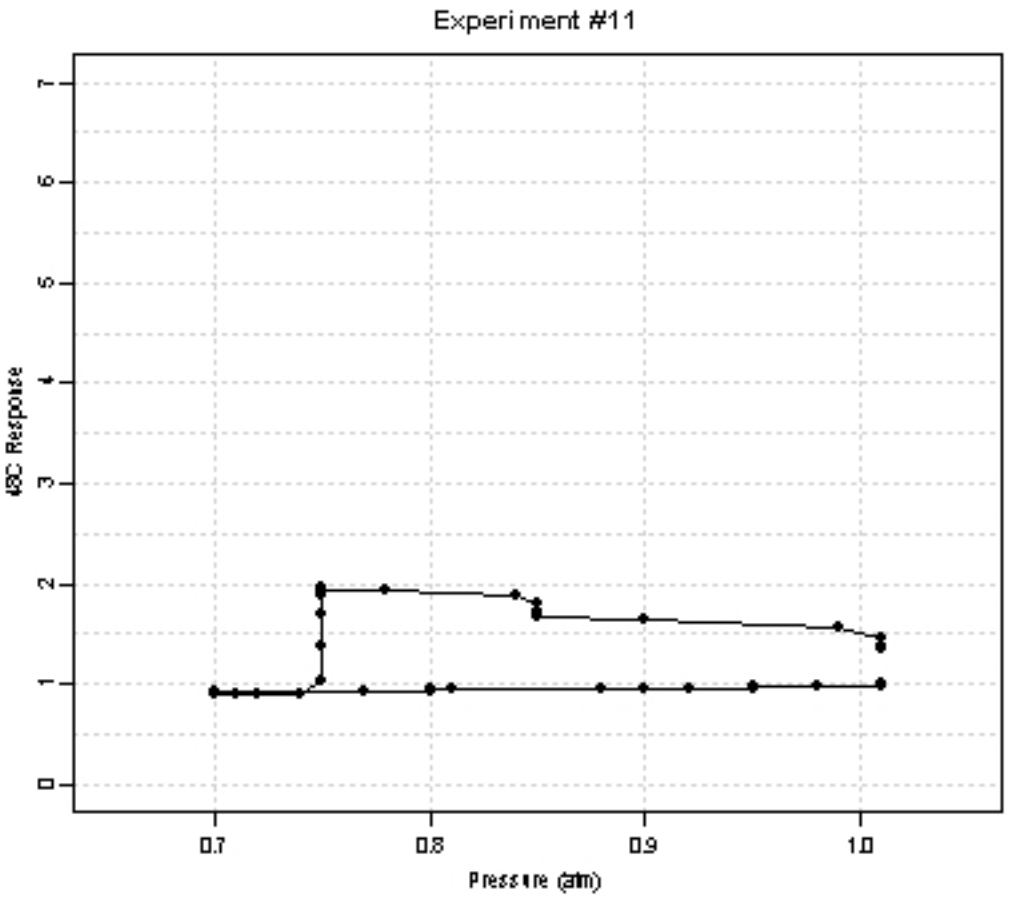
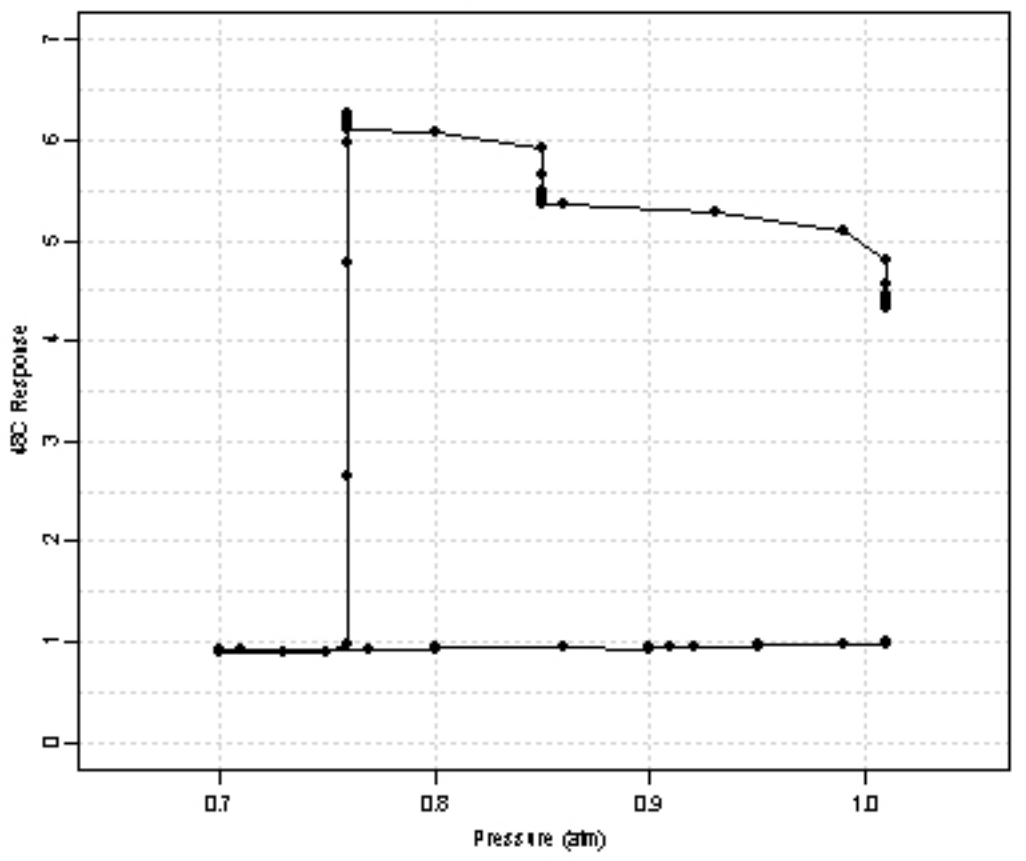
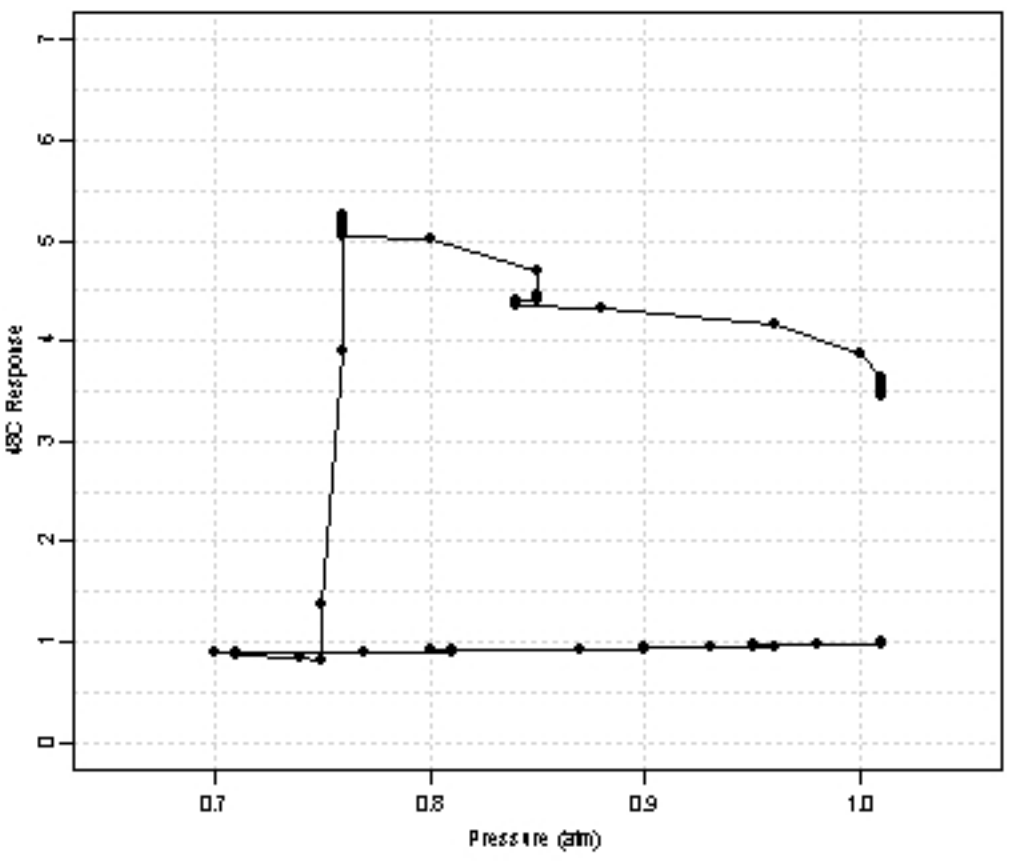


Fig. D13 CO/CO2 Tests: Variable Pressure #1: 48C/48C CO (Expts 10-14)









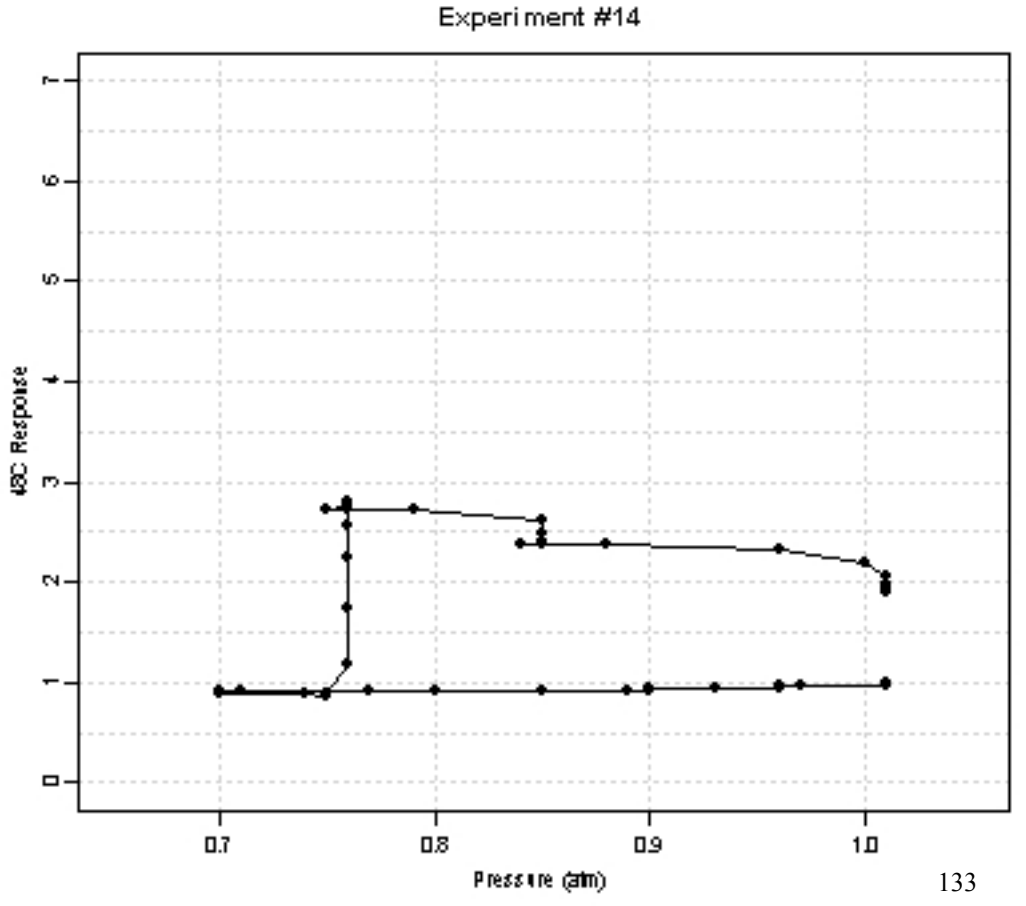
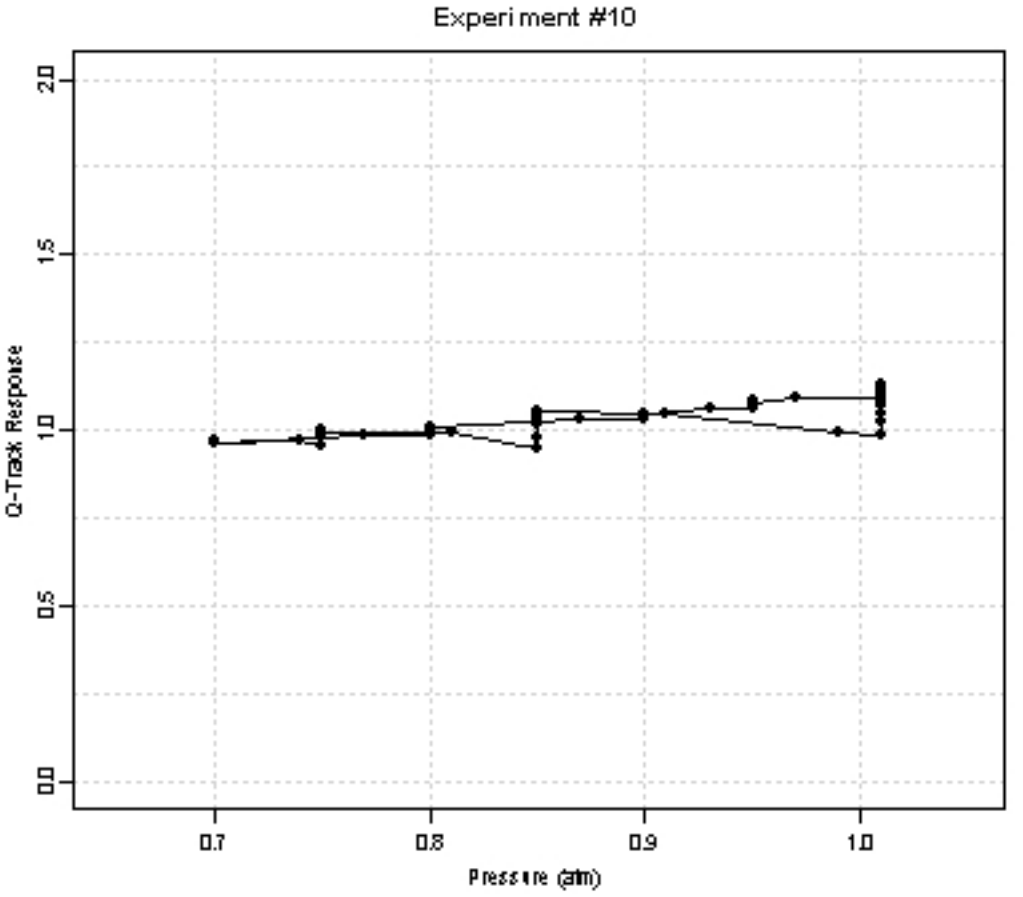
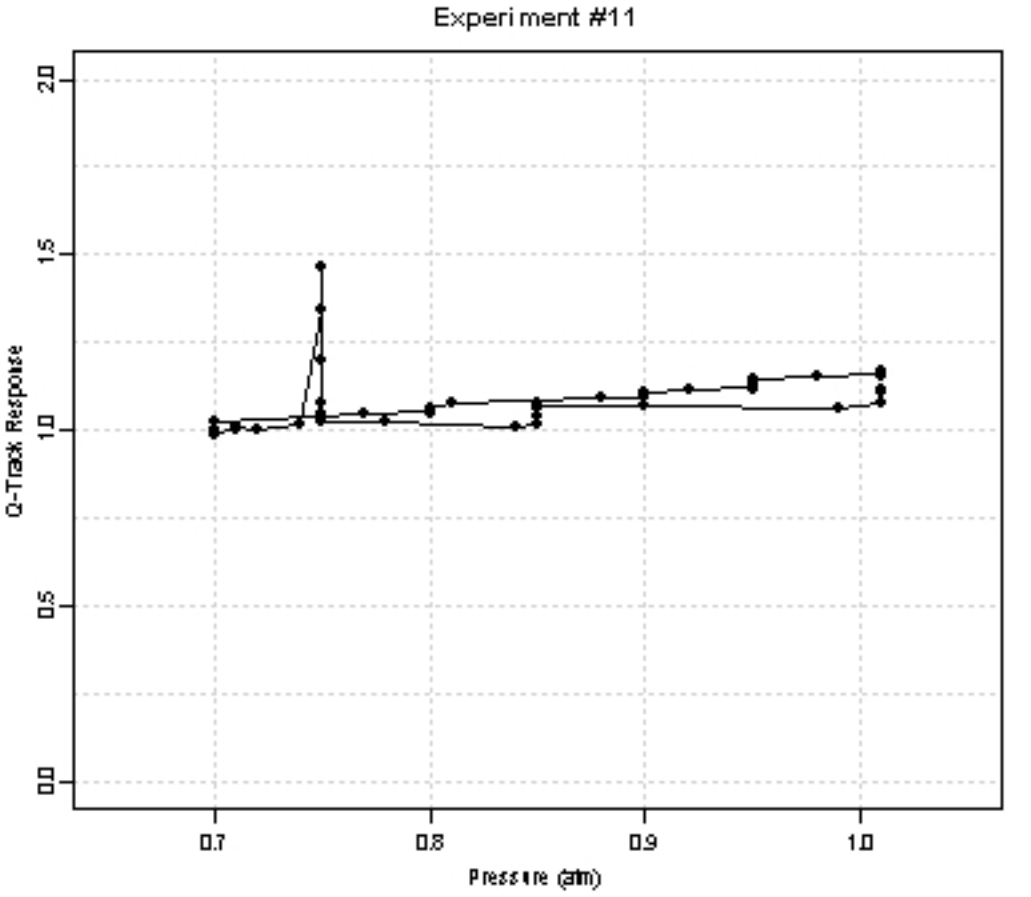
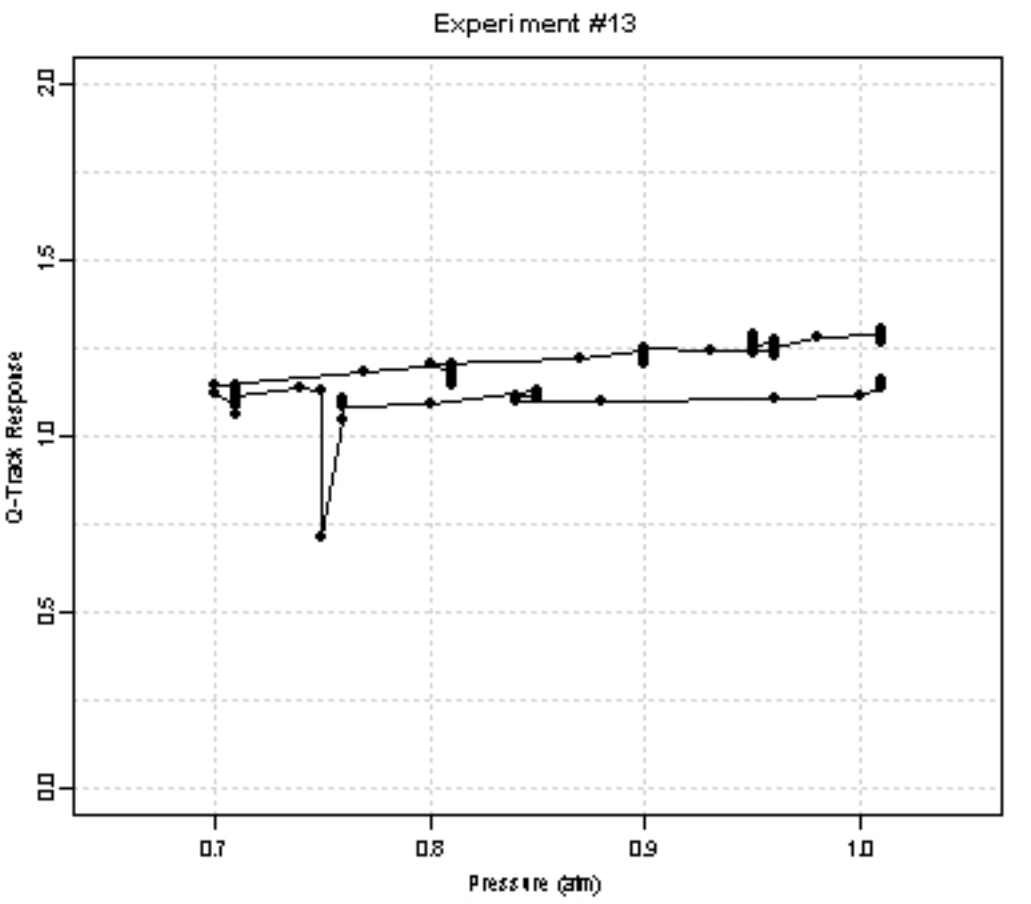


Fig. D14 CO/CO2 Tests: Variable Pressure #1: Q-Track/48C CO (Expts 10-14)







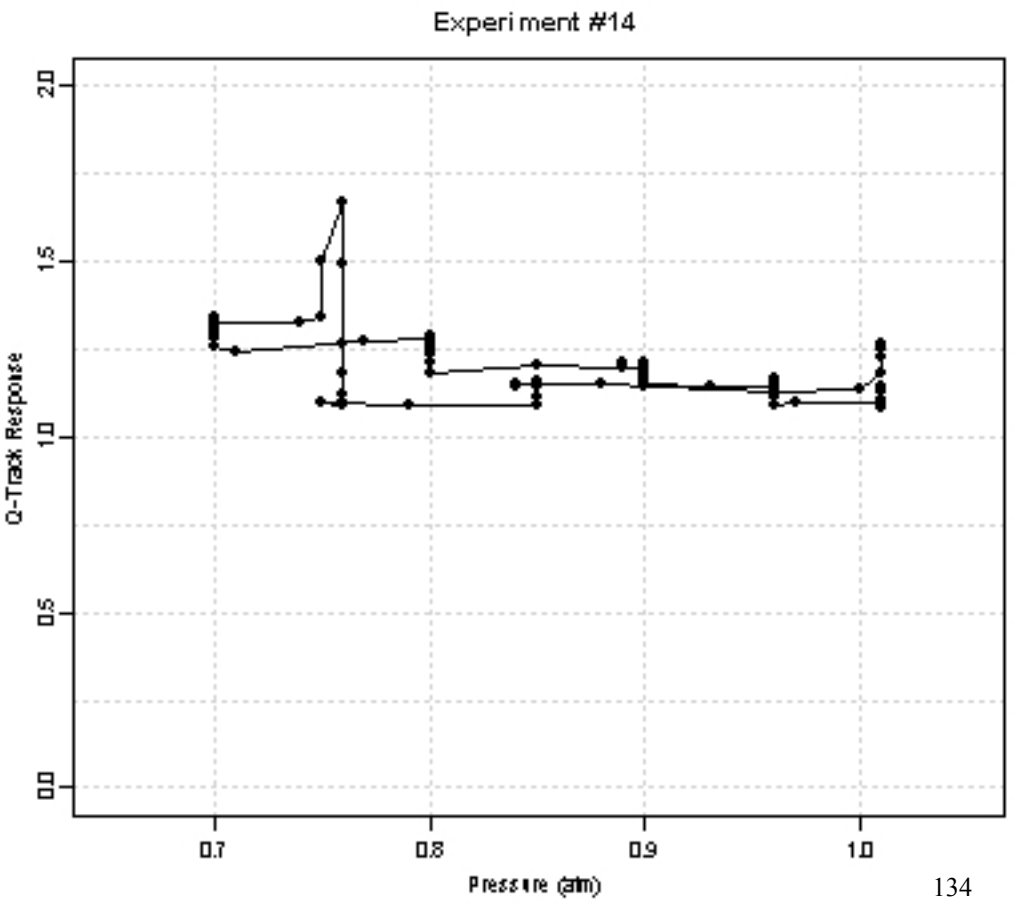
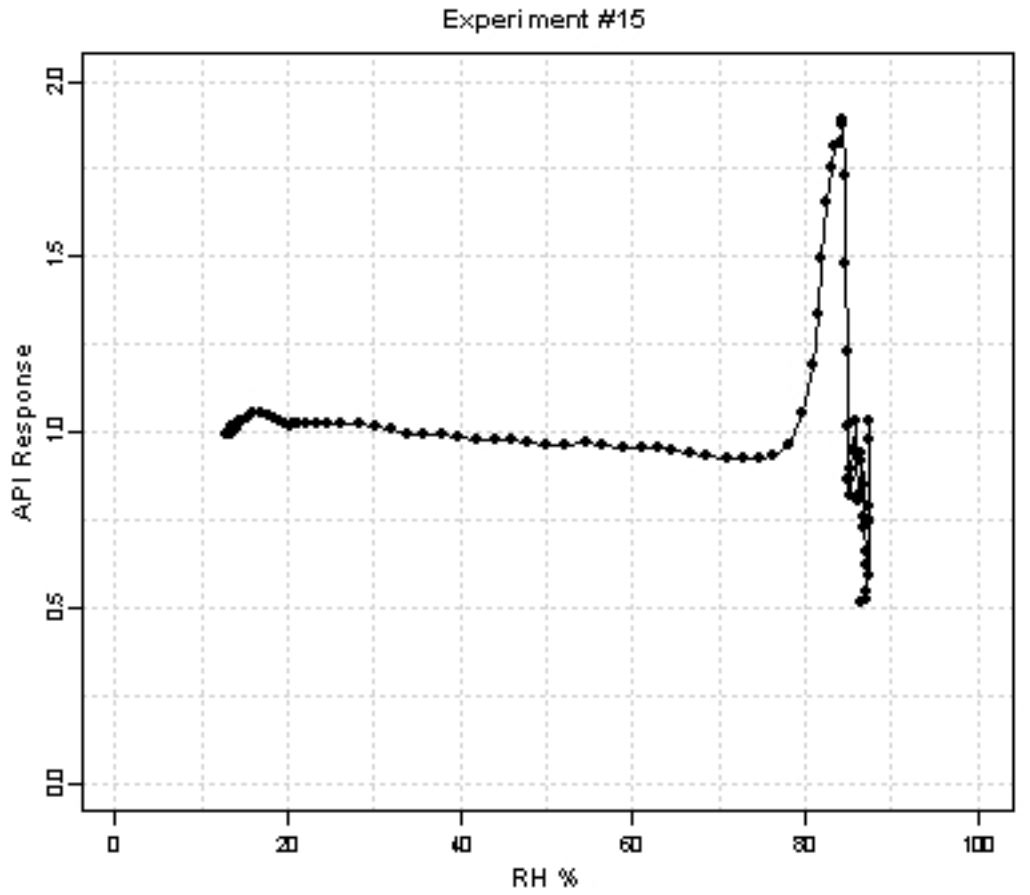
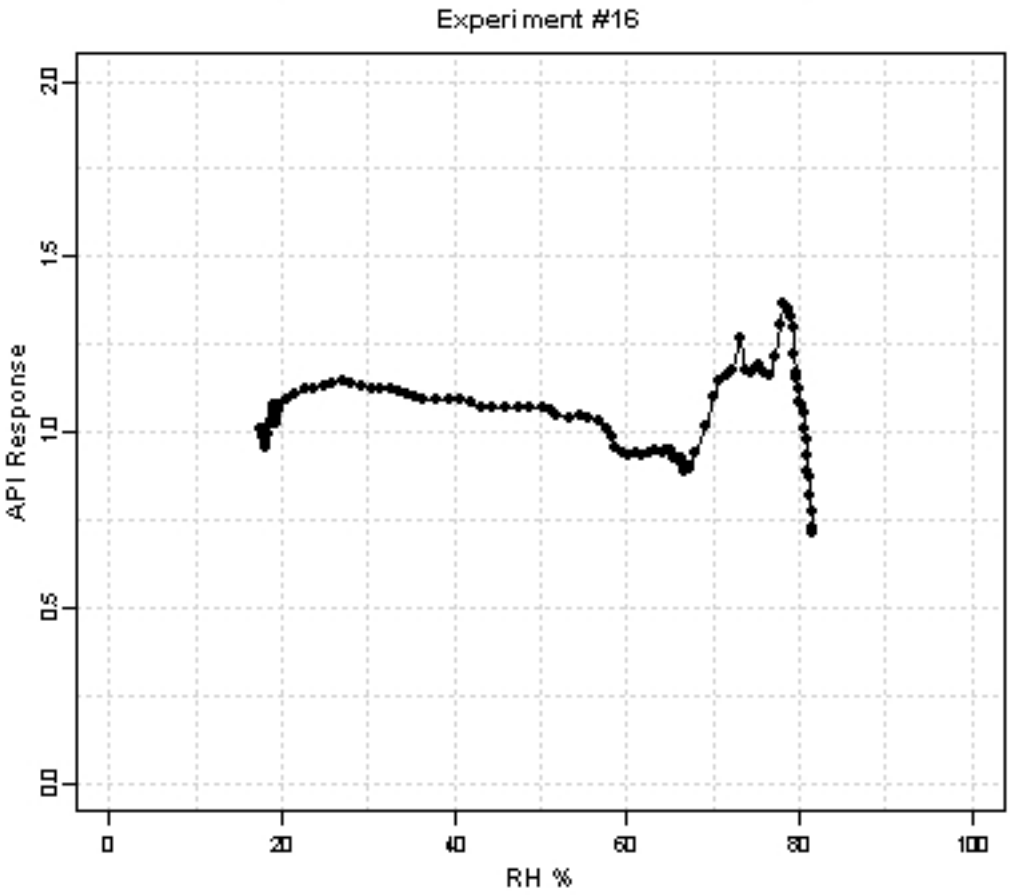
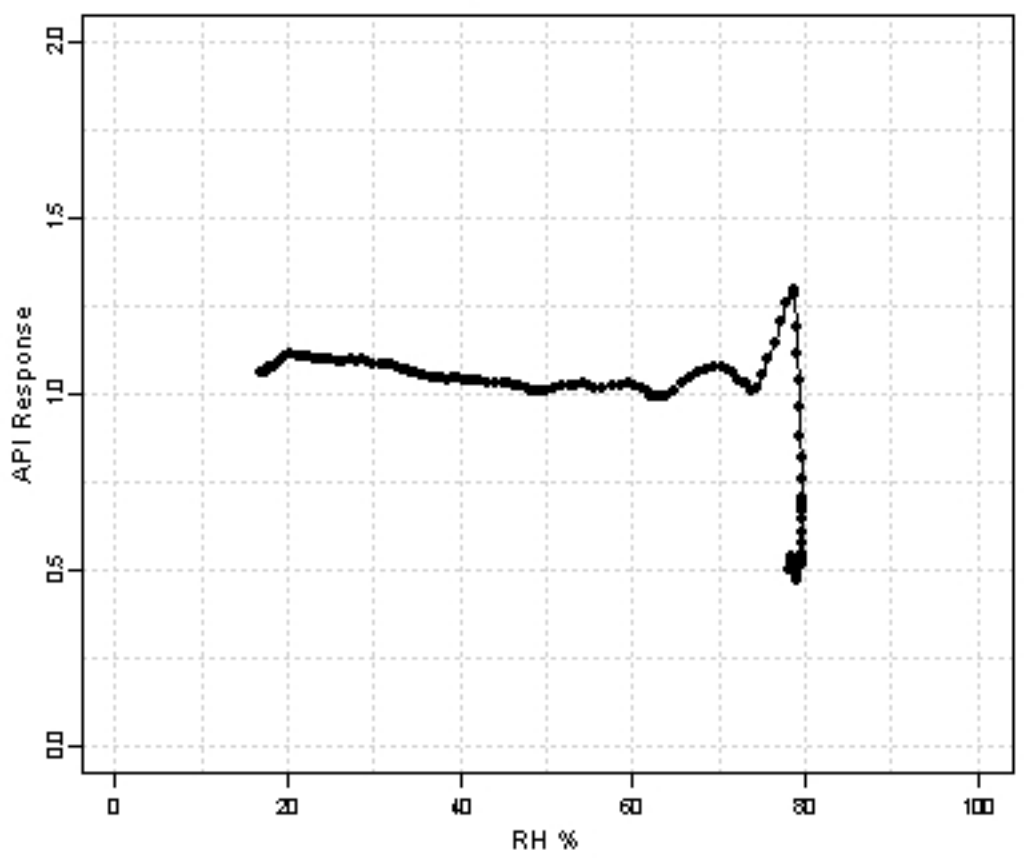
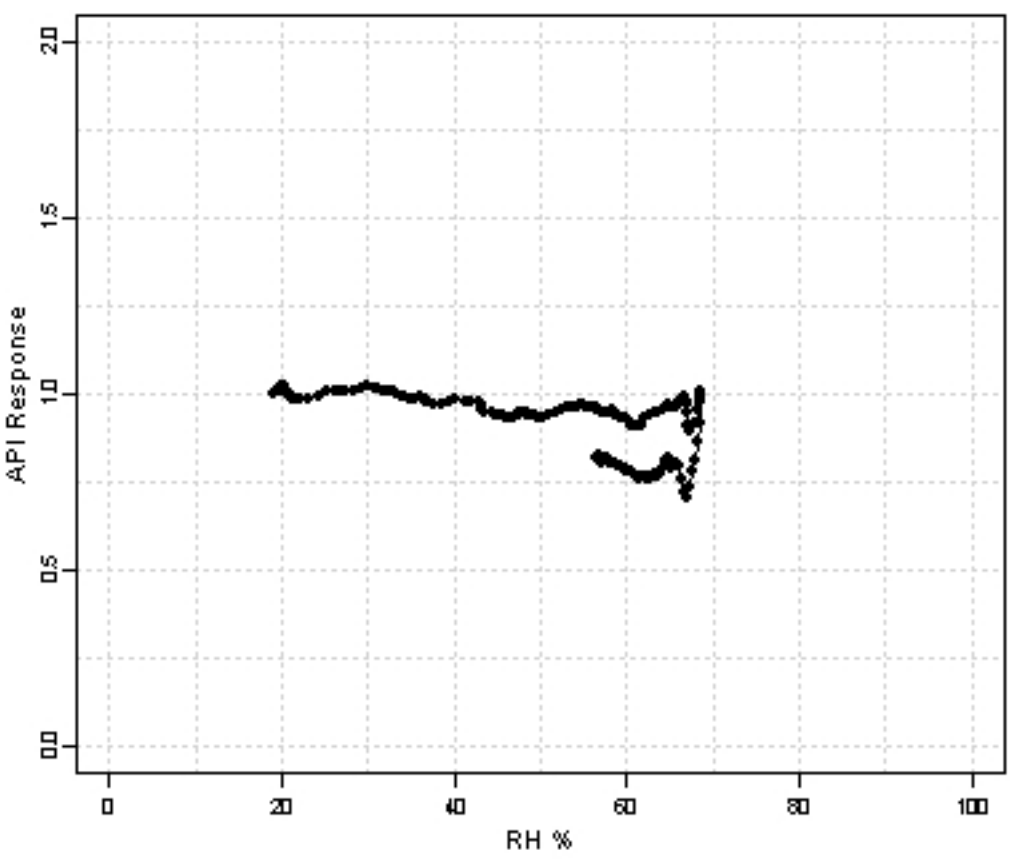


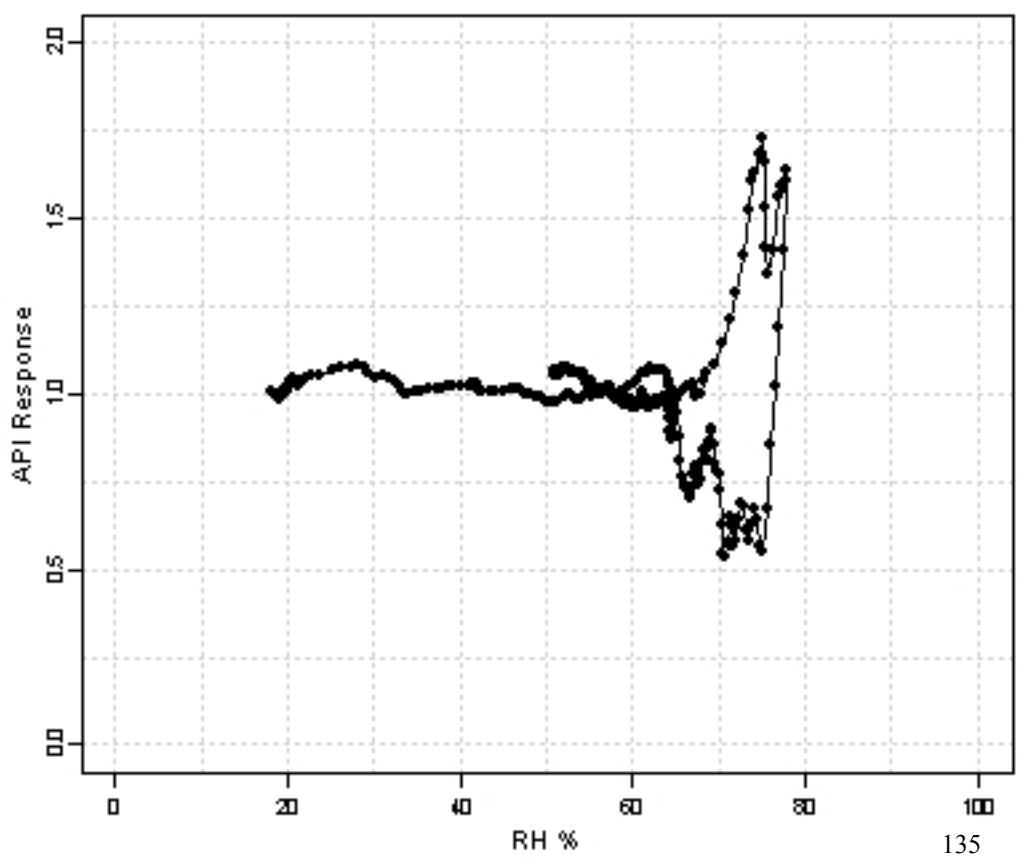
Fig. D15 Ozone Tests: Variable Relative Humidity: API/API (Expts 15-20)











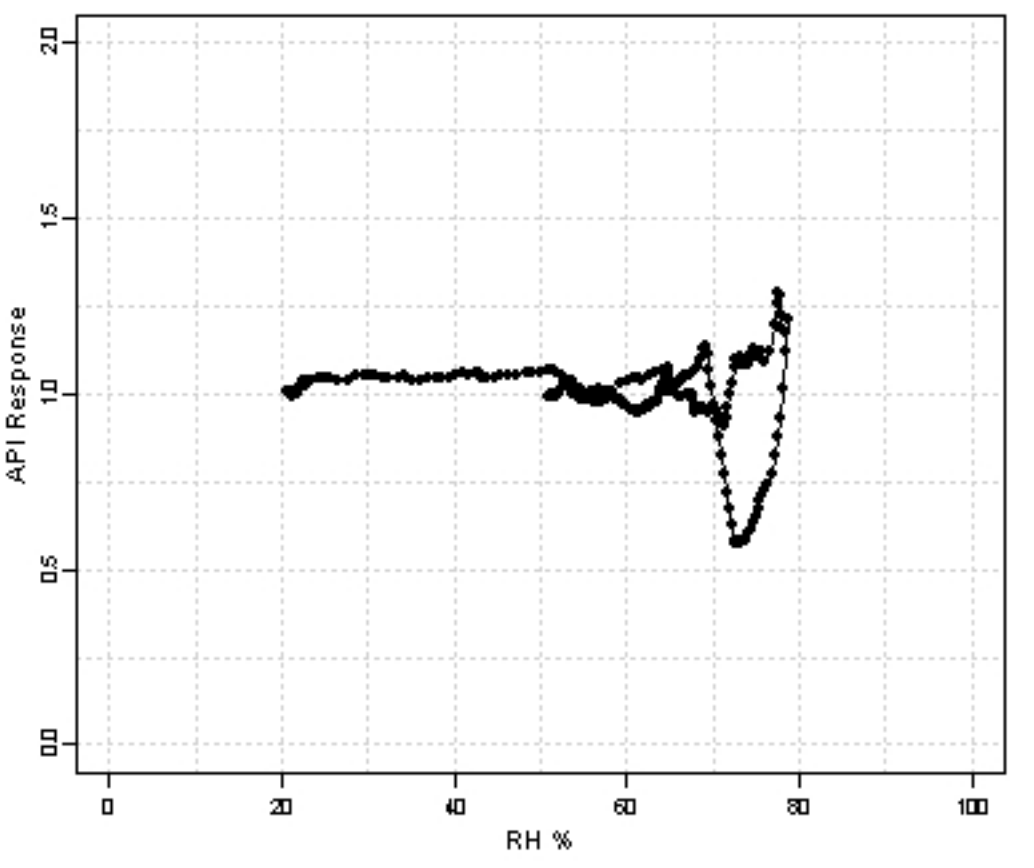
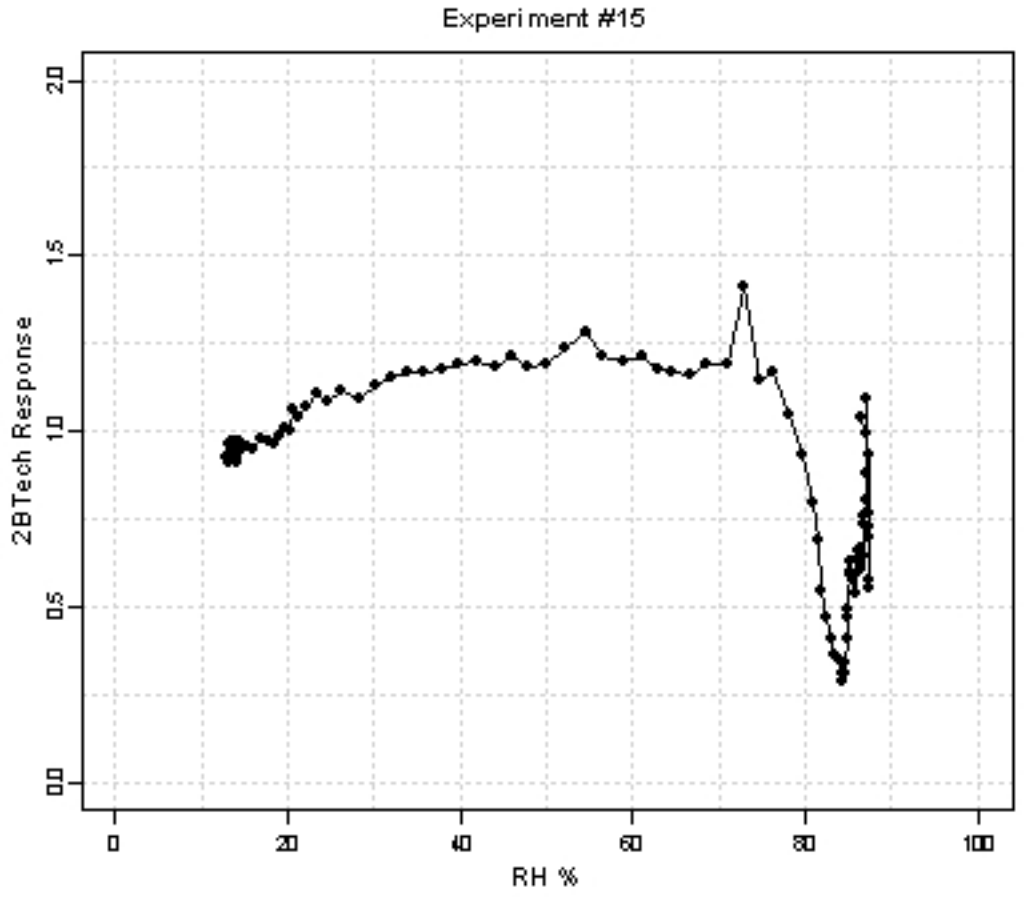
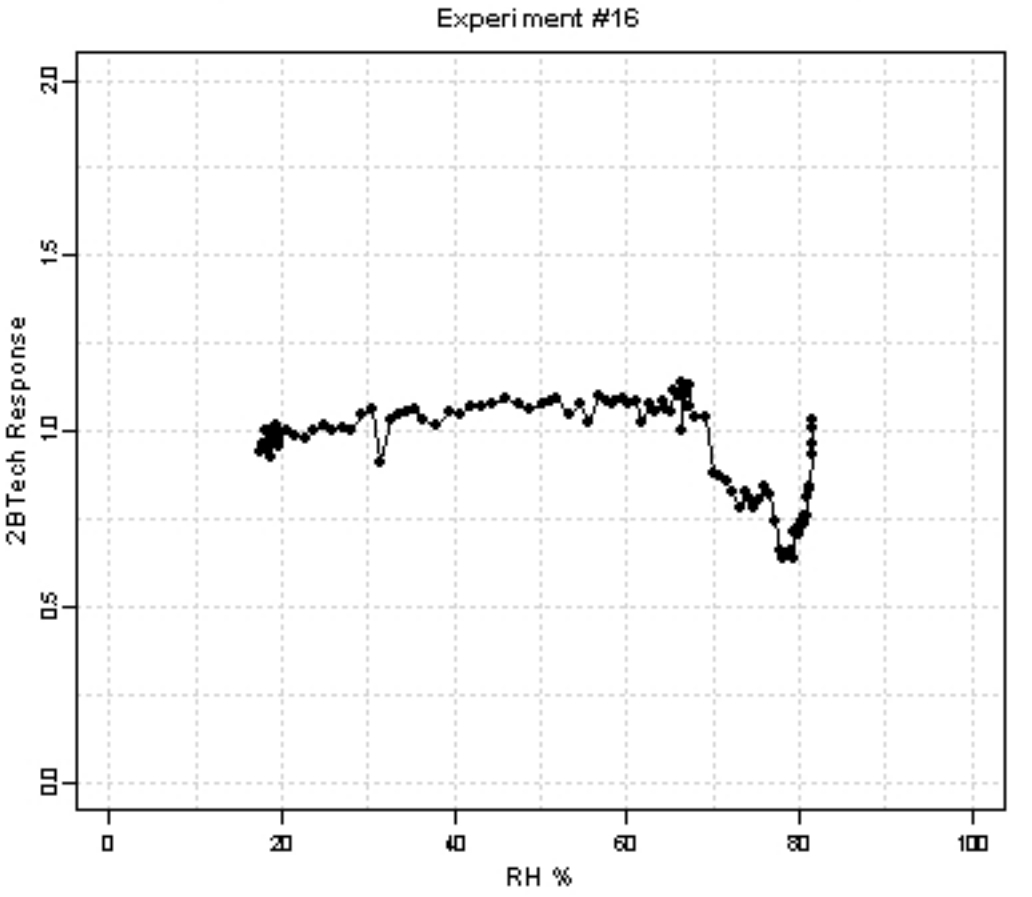
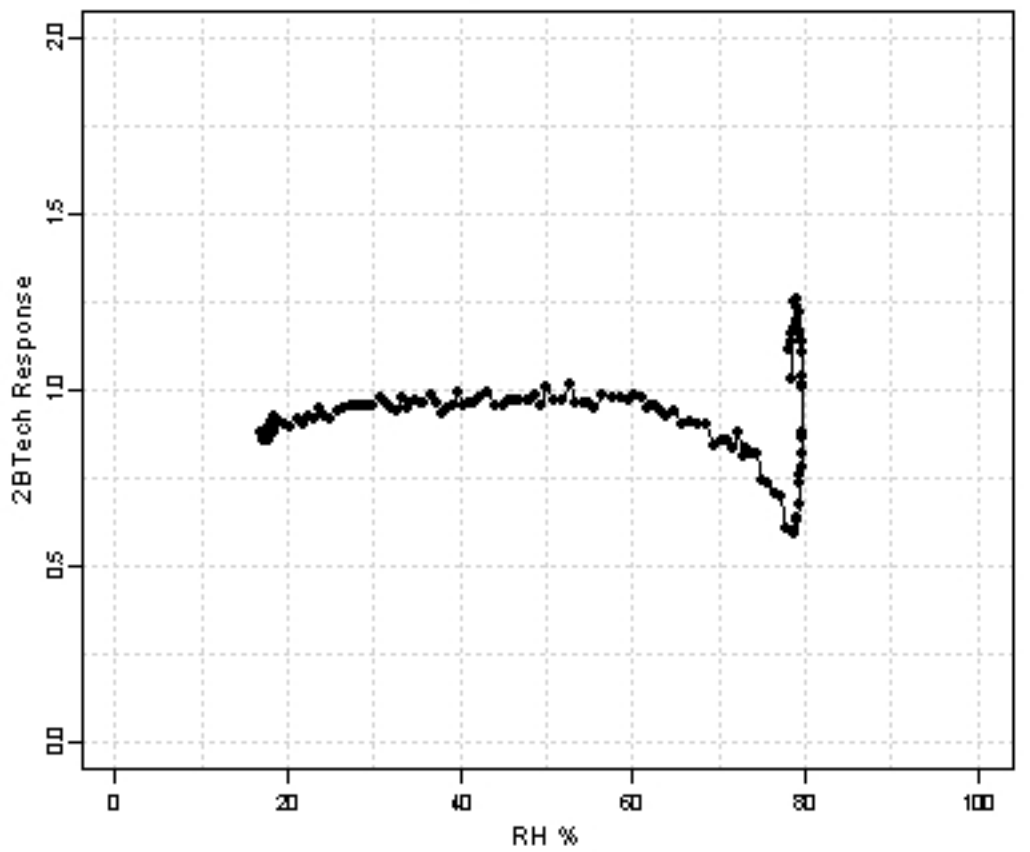
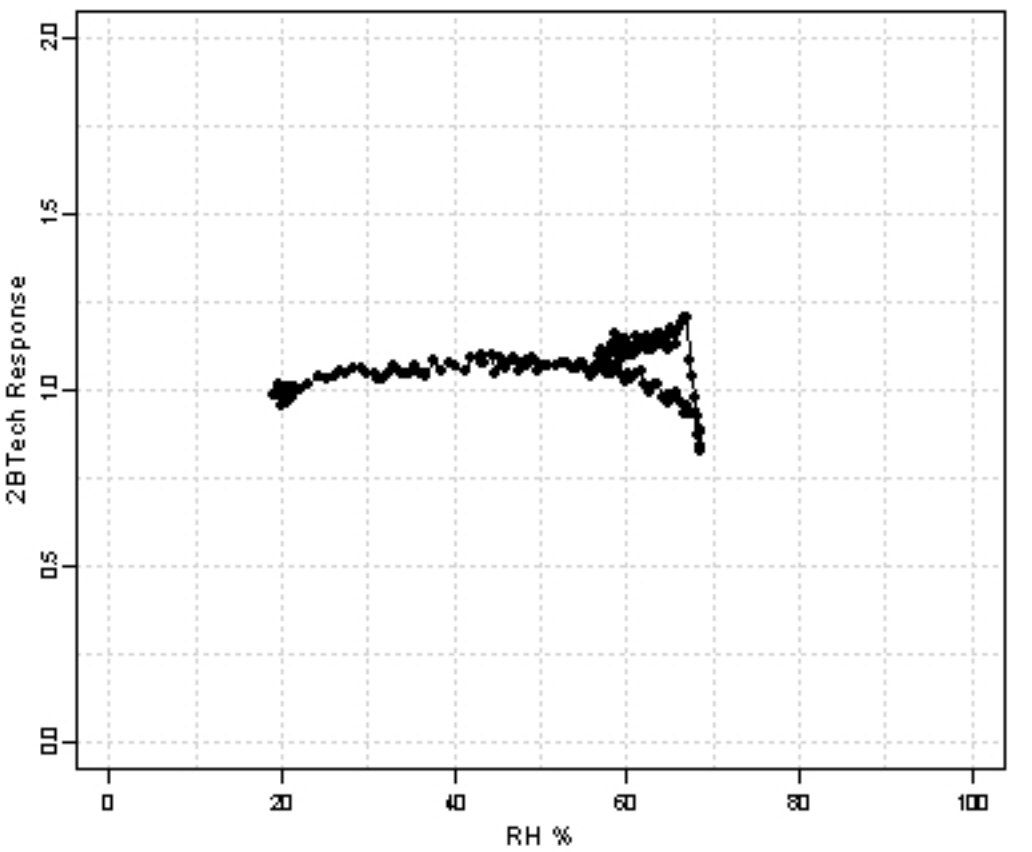


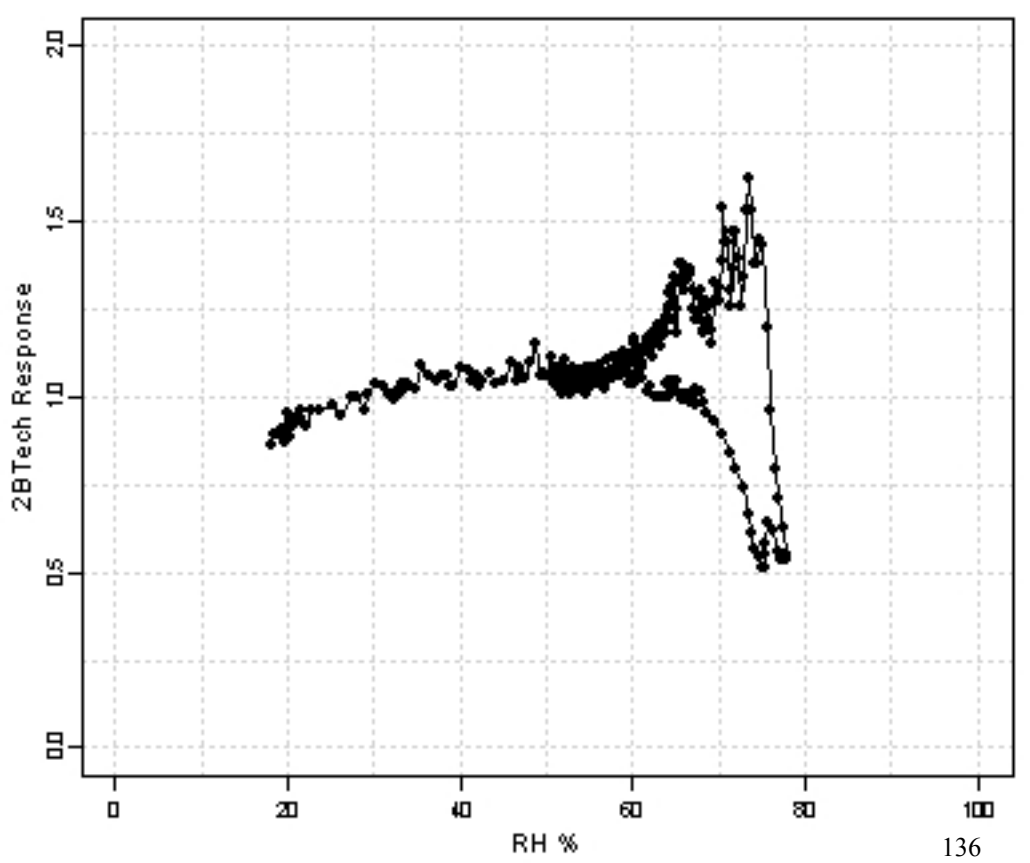
Fig. D16 Ozone Tests: Variable Relative Humidity: 2BTech/API (Expts 15-20)











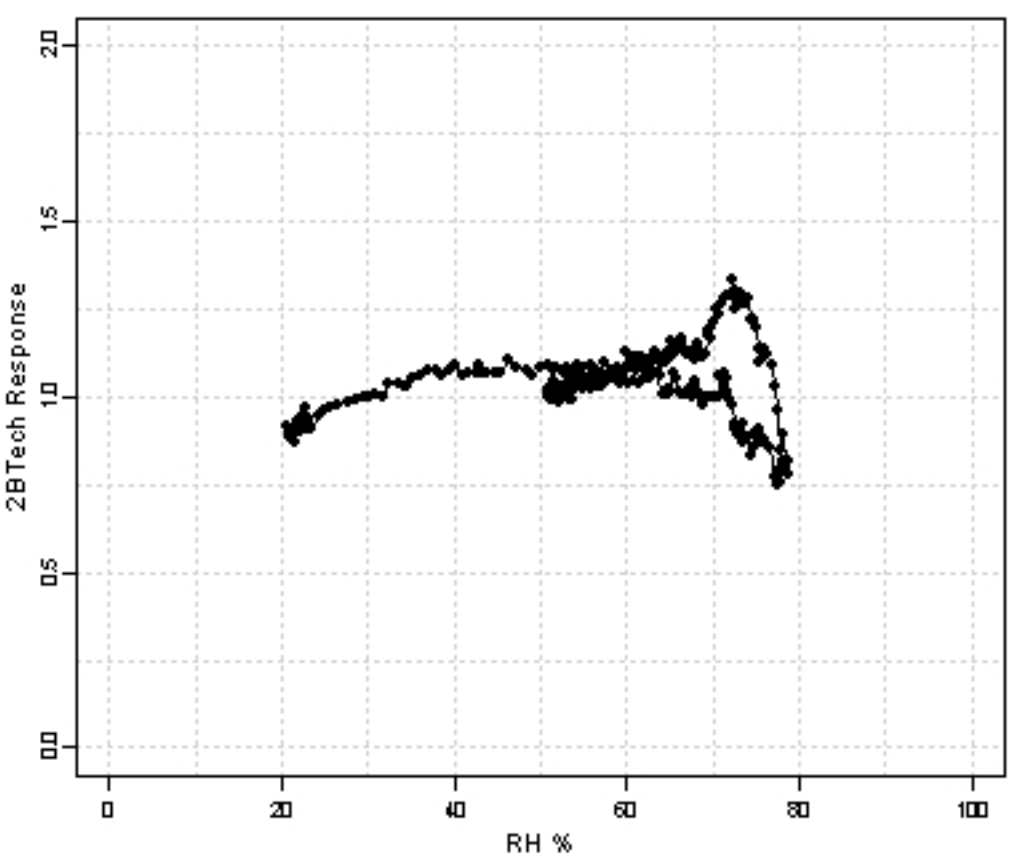
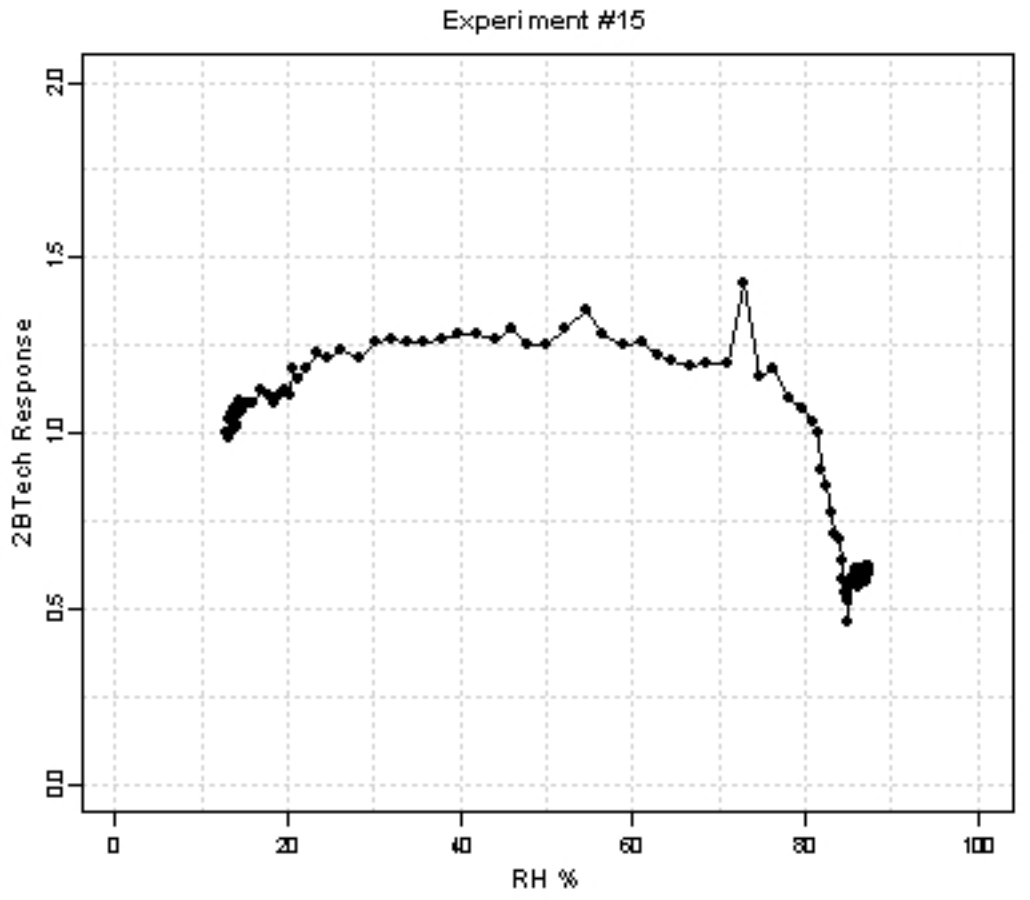
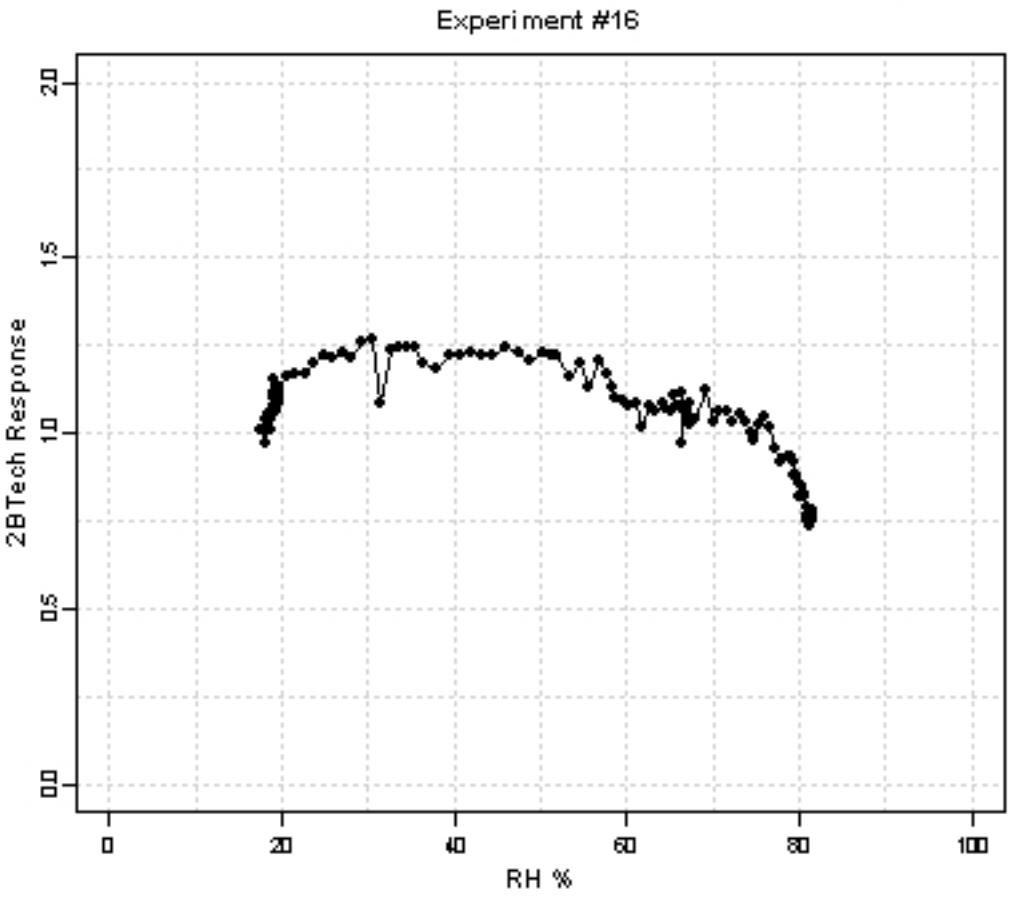
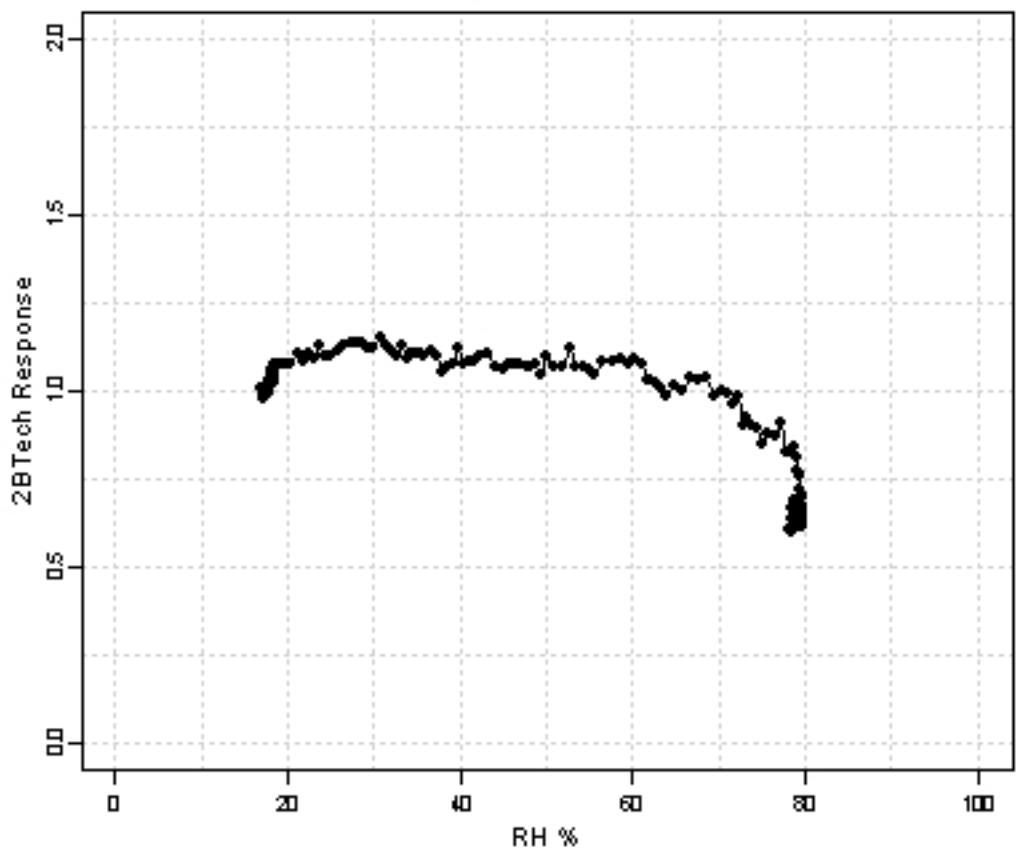
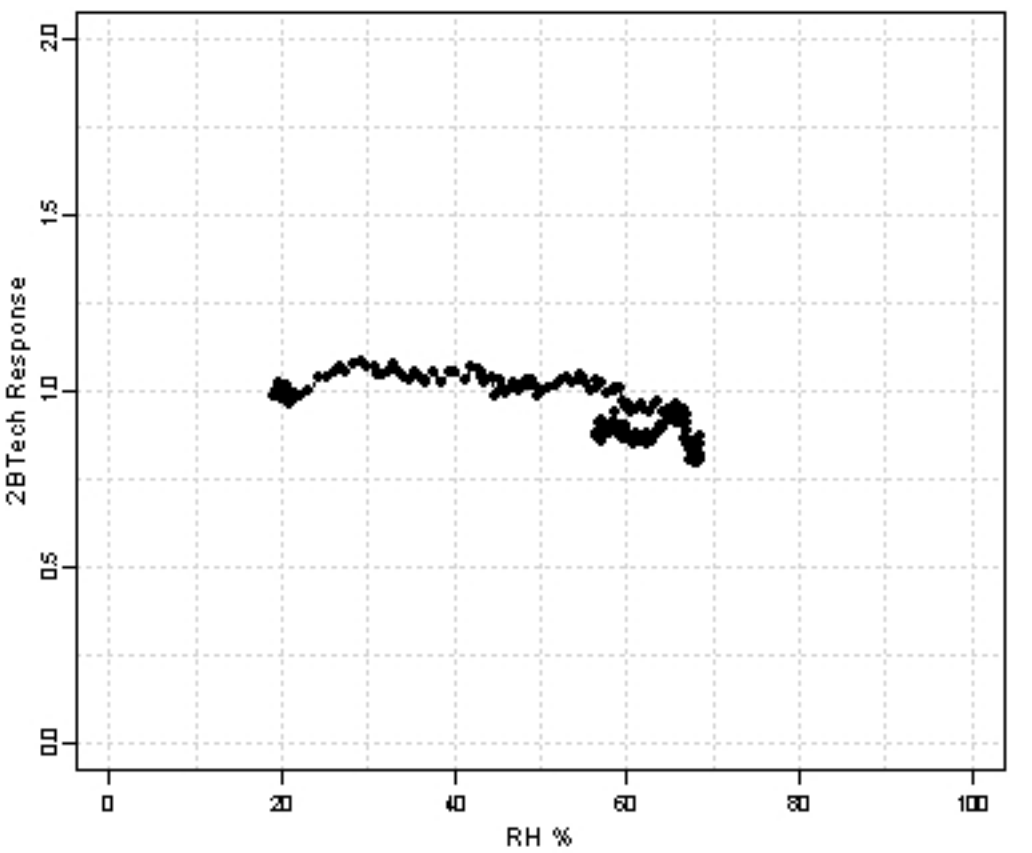


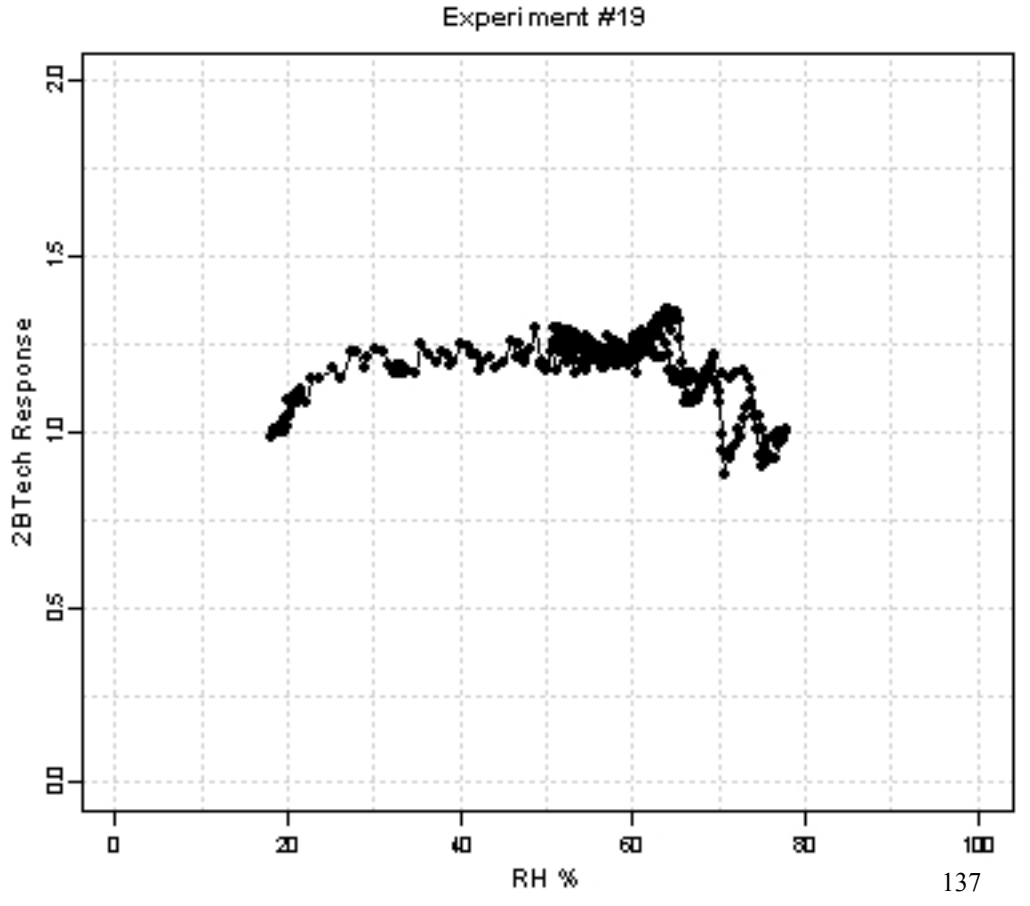
Fig. D17 Ozone Tests: Variable Relative Humidity: 2BTech/2BTech (Expts 15-20)











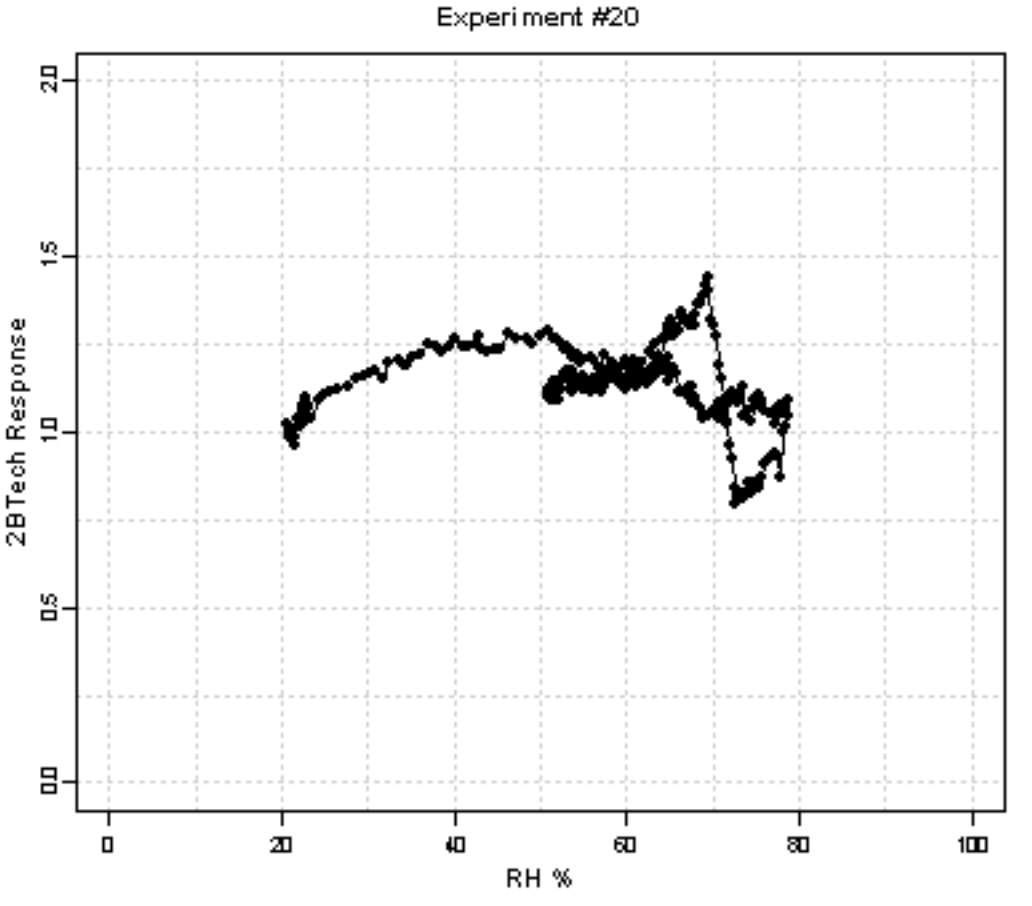
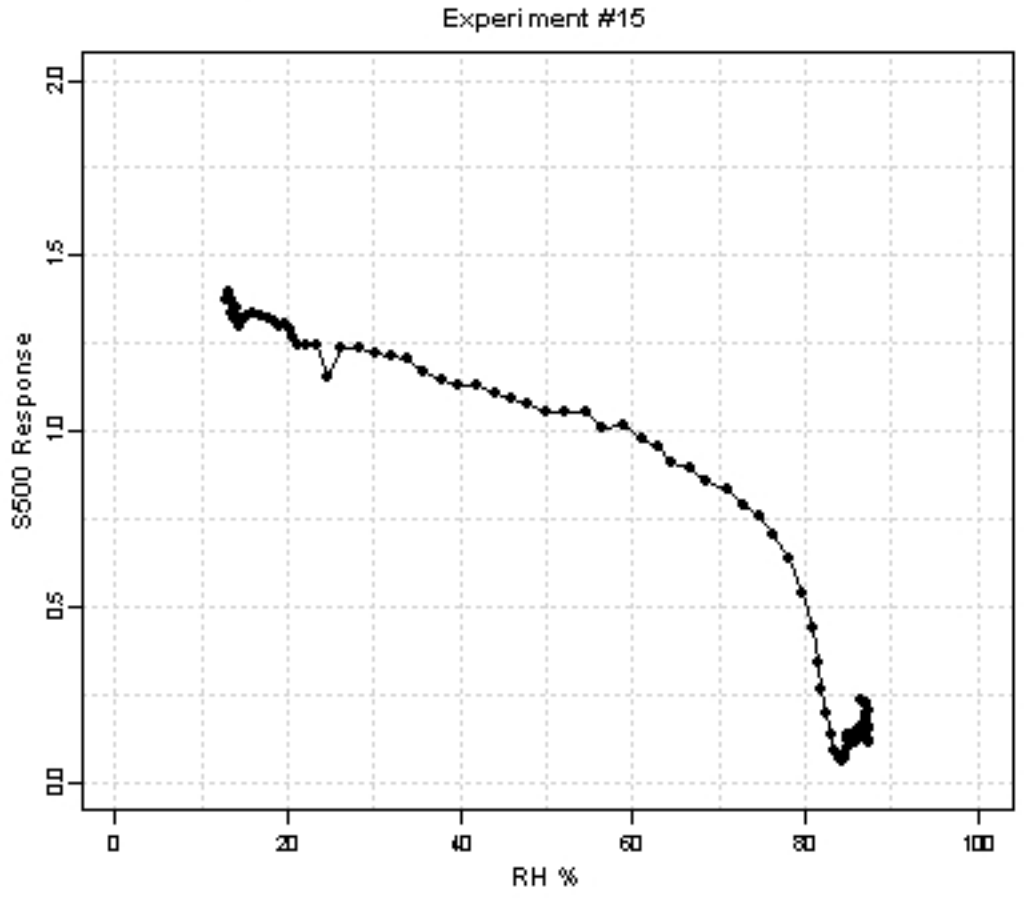
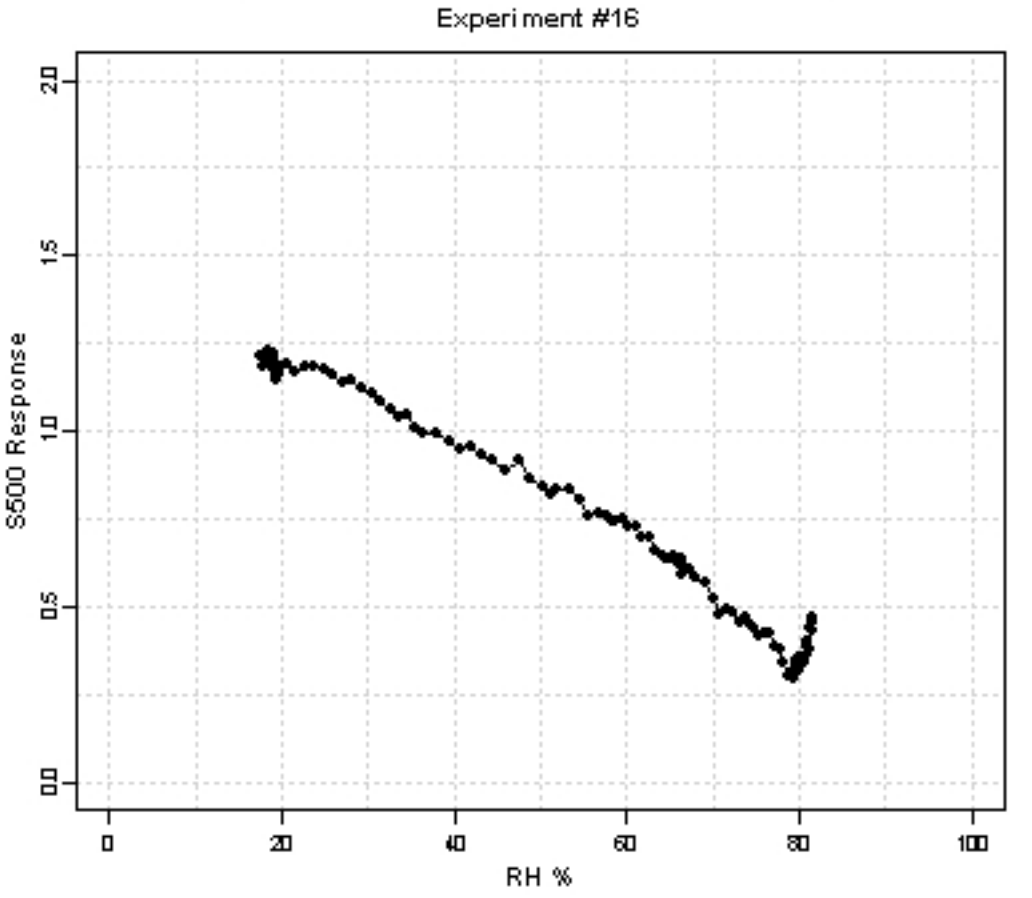
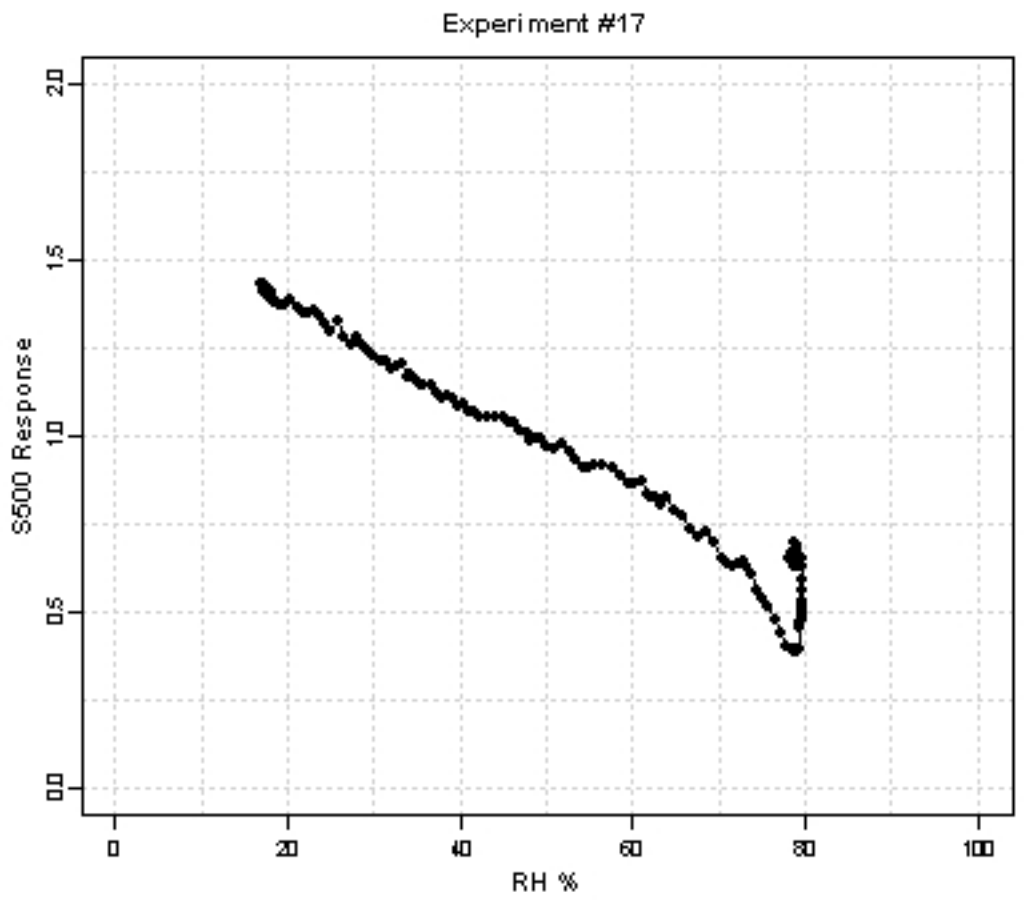
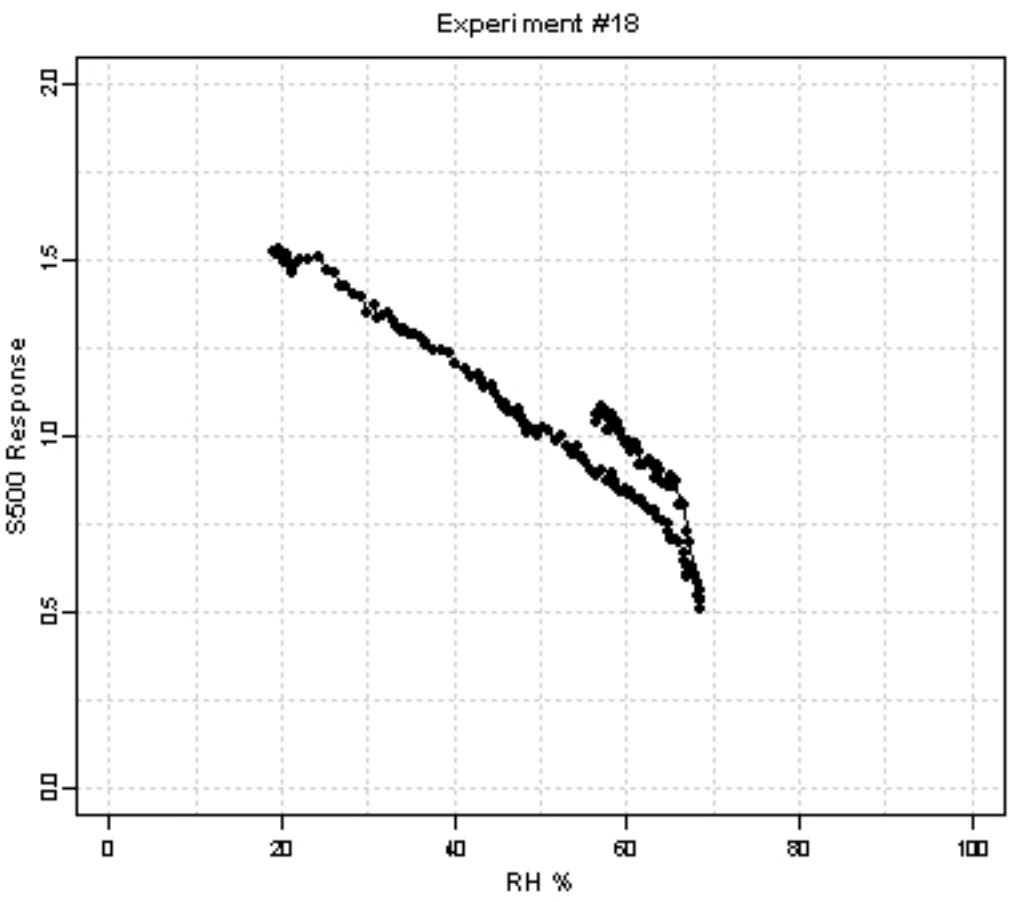


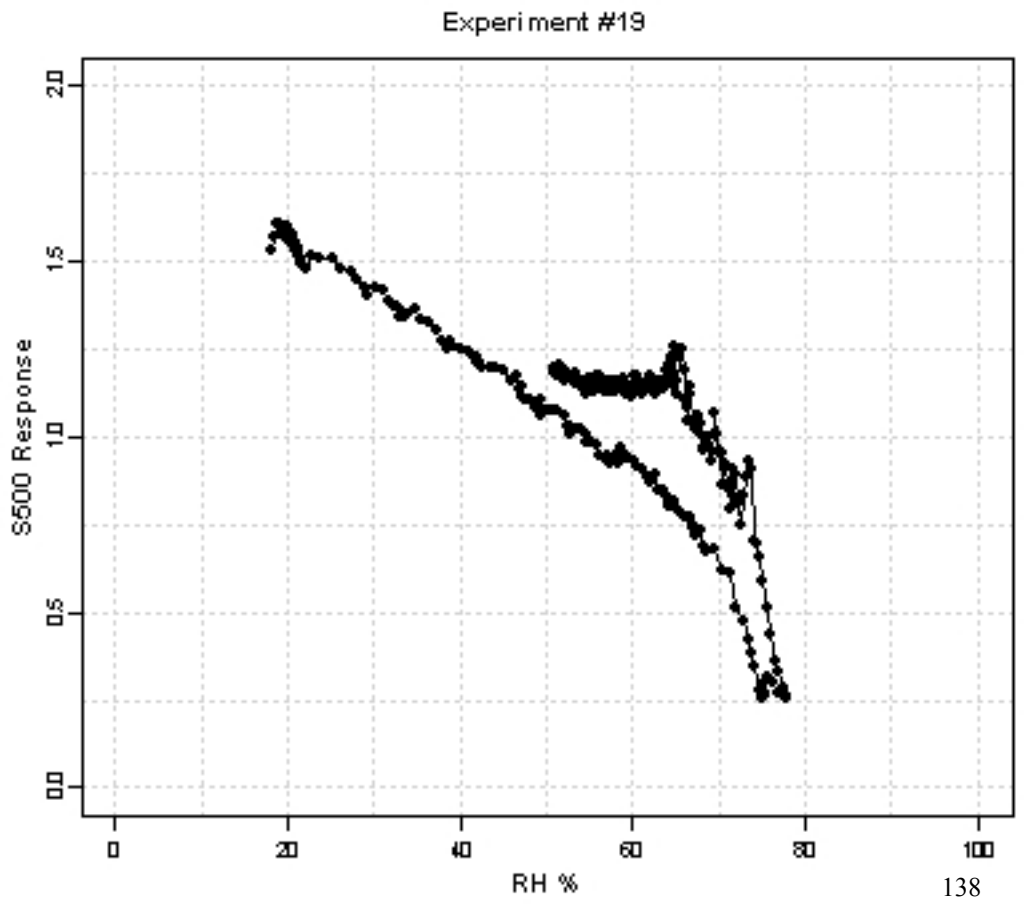
Fig. D18 Ozone Tests: Variable Relative Humidity: S500/API (Expts 15-20)











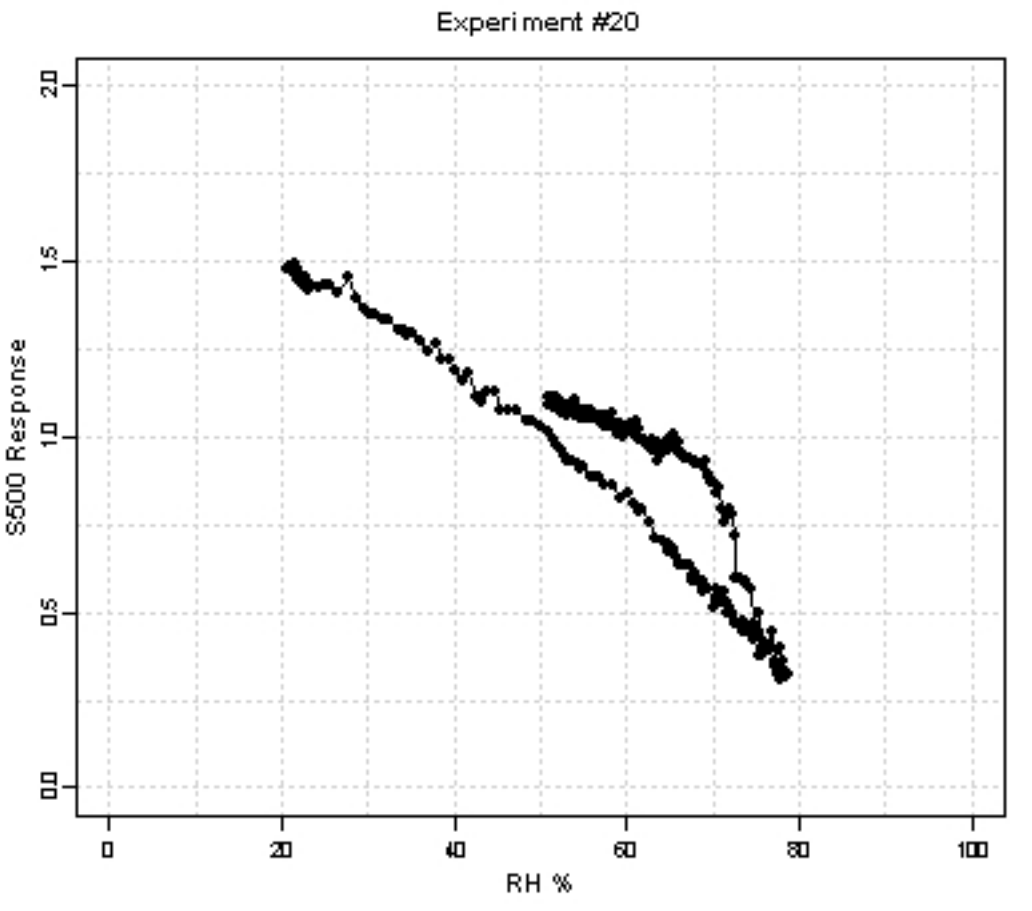
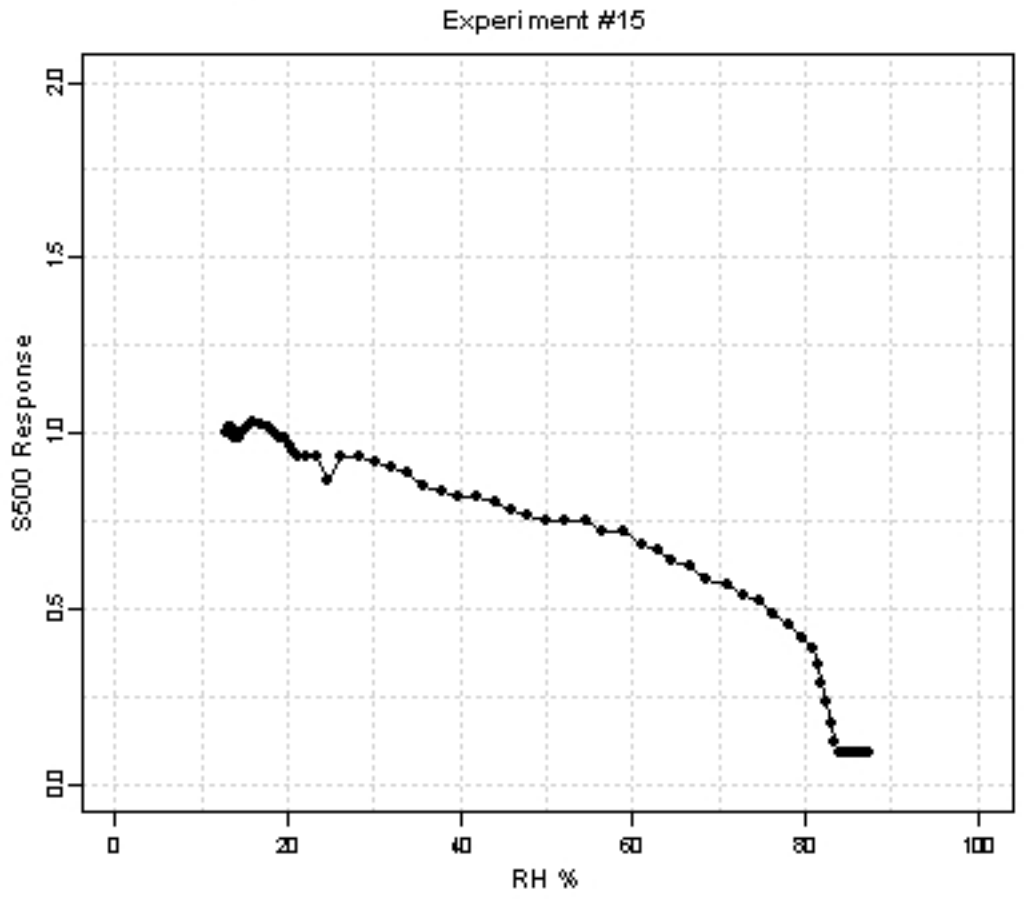
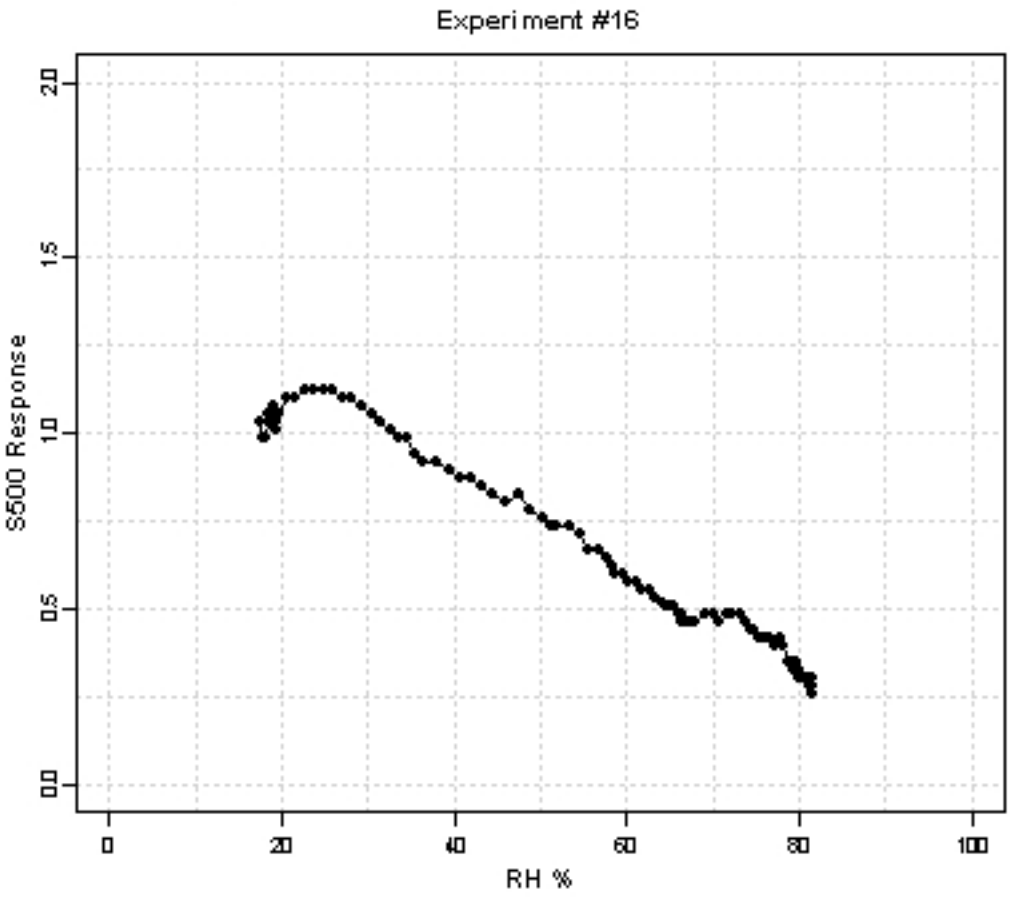
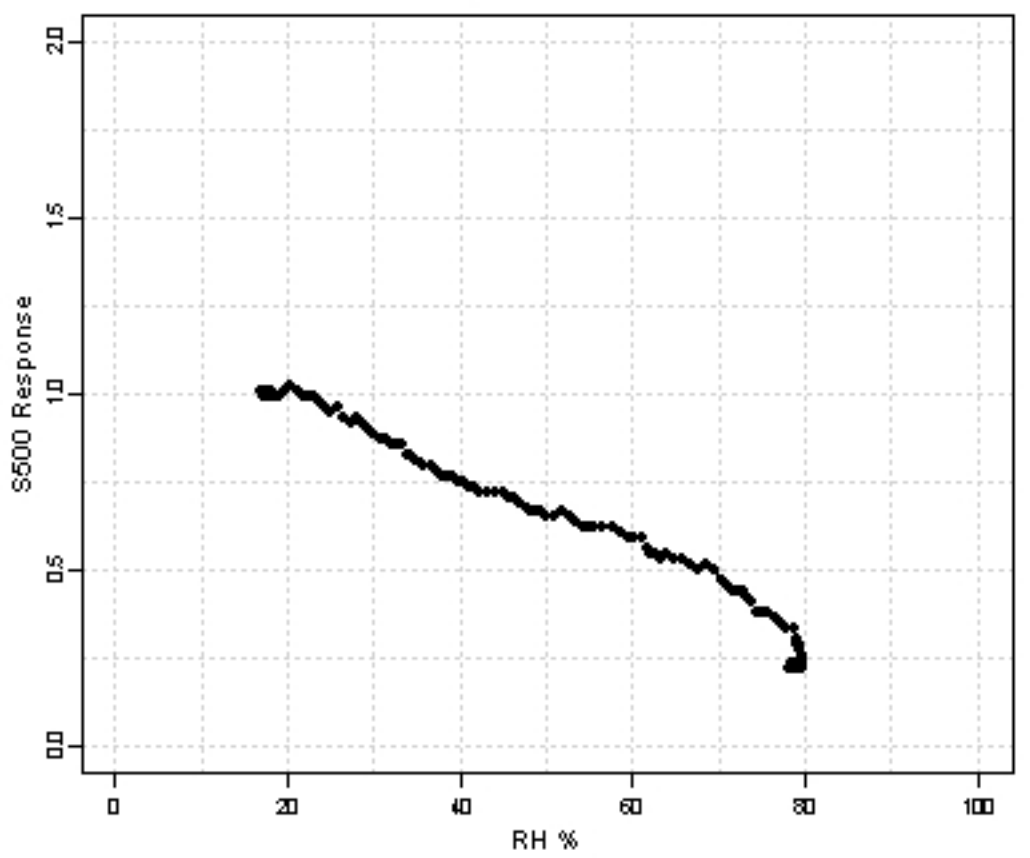
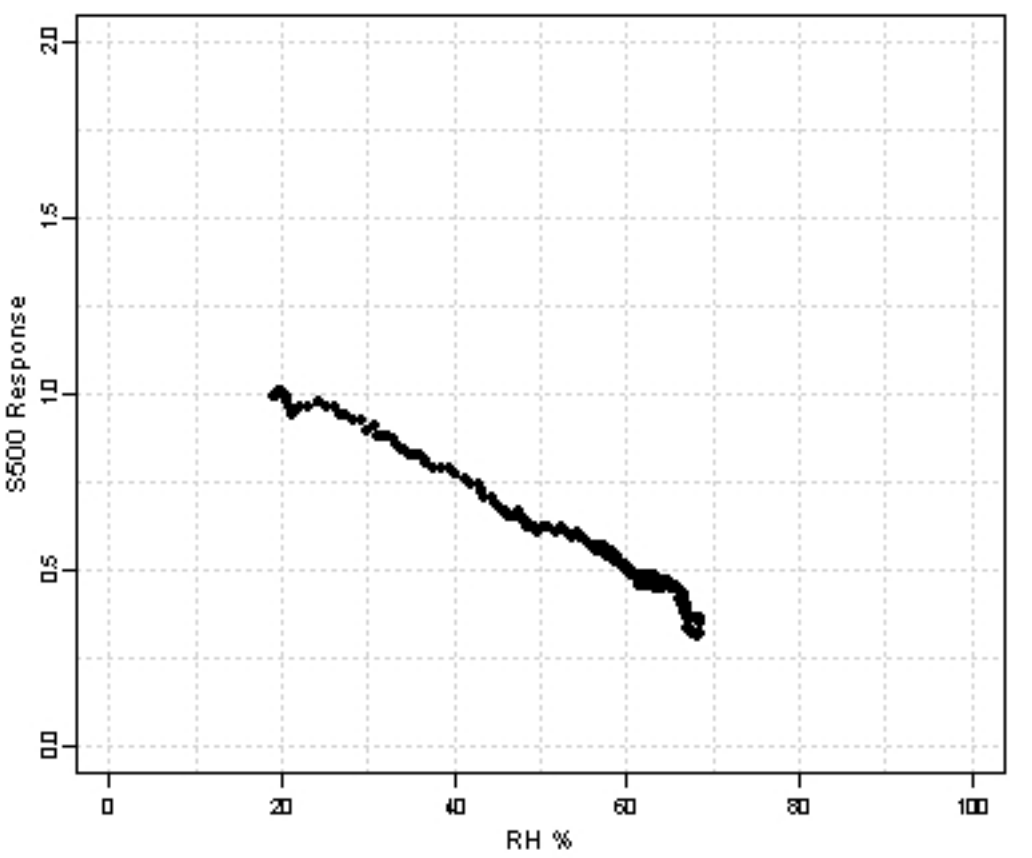


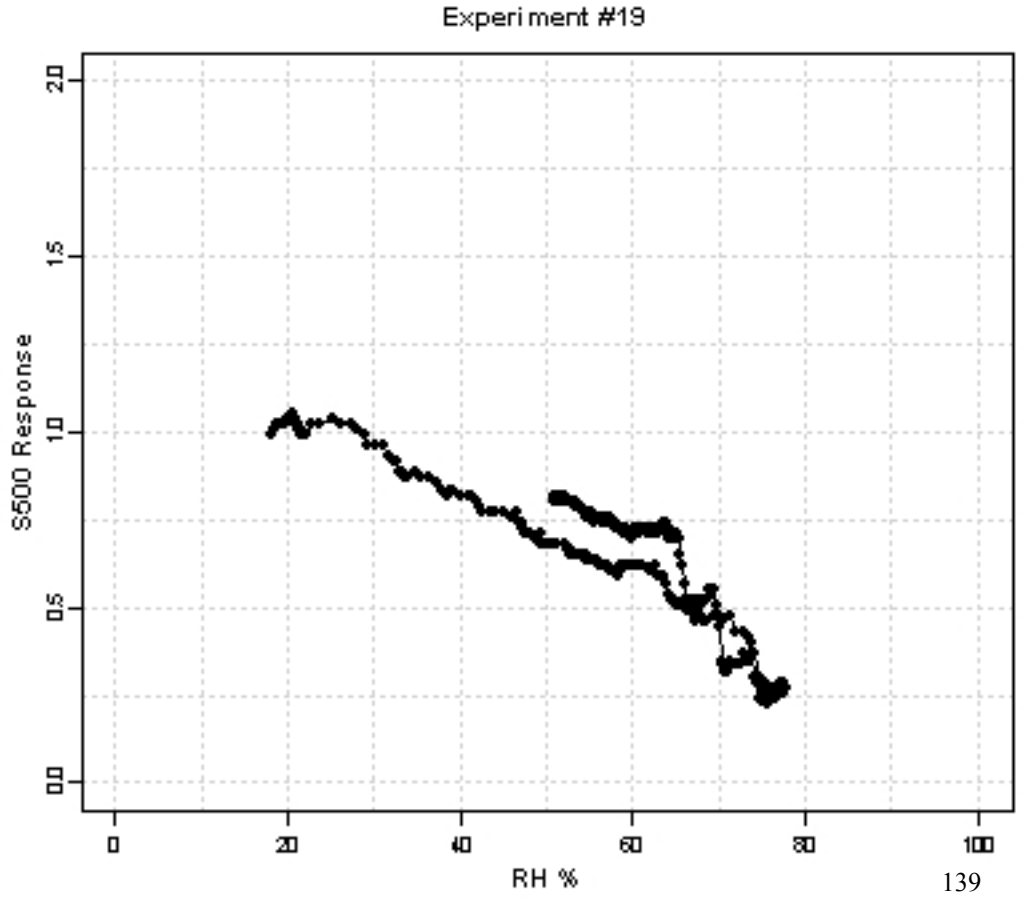
Fig. D19 Ozone Tests: Variable Relative Humidity: S500/S500 (Expts 15-20)











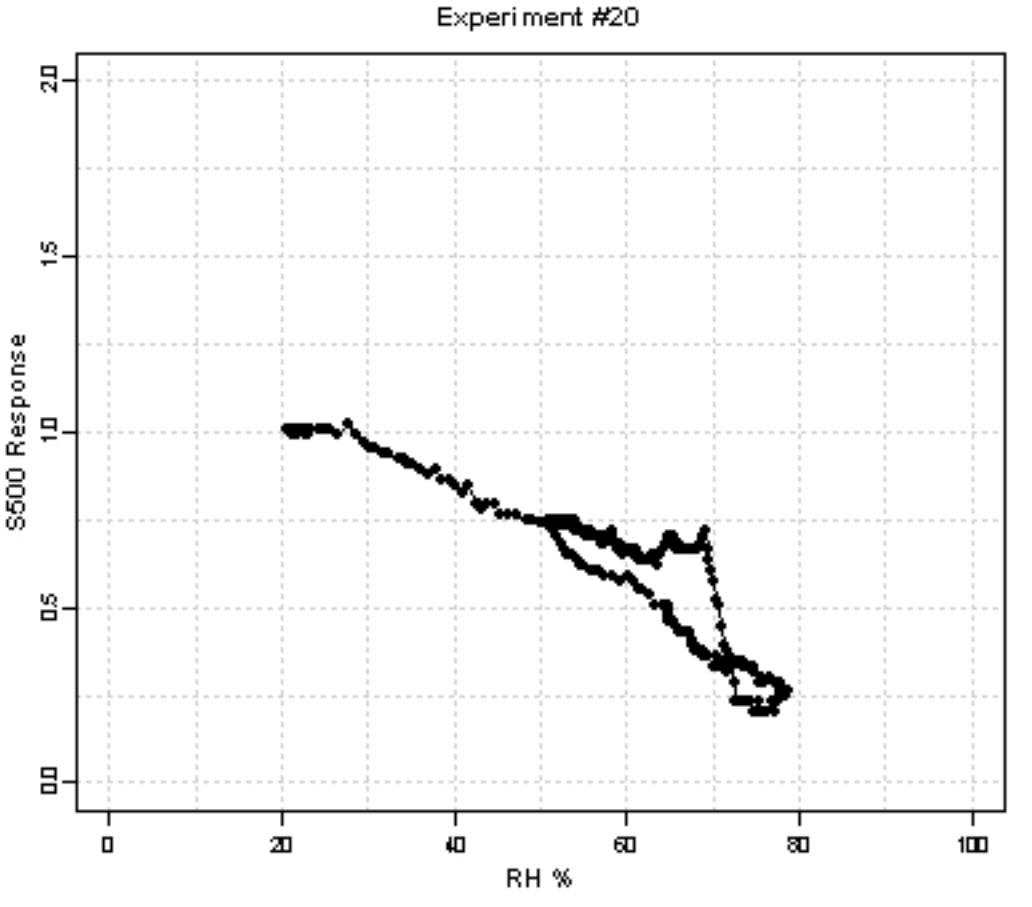
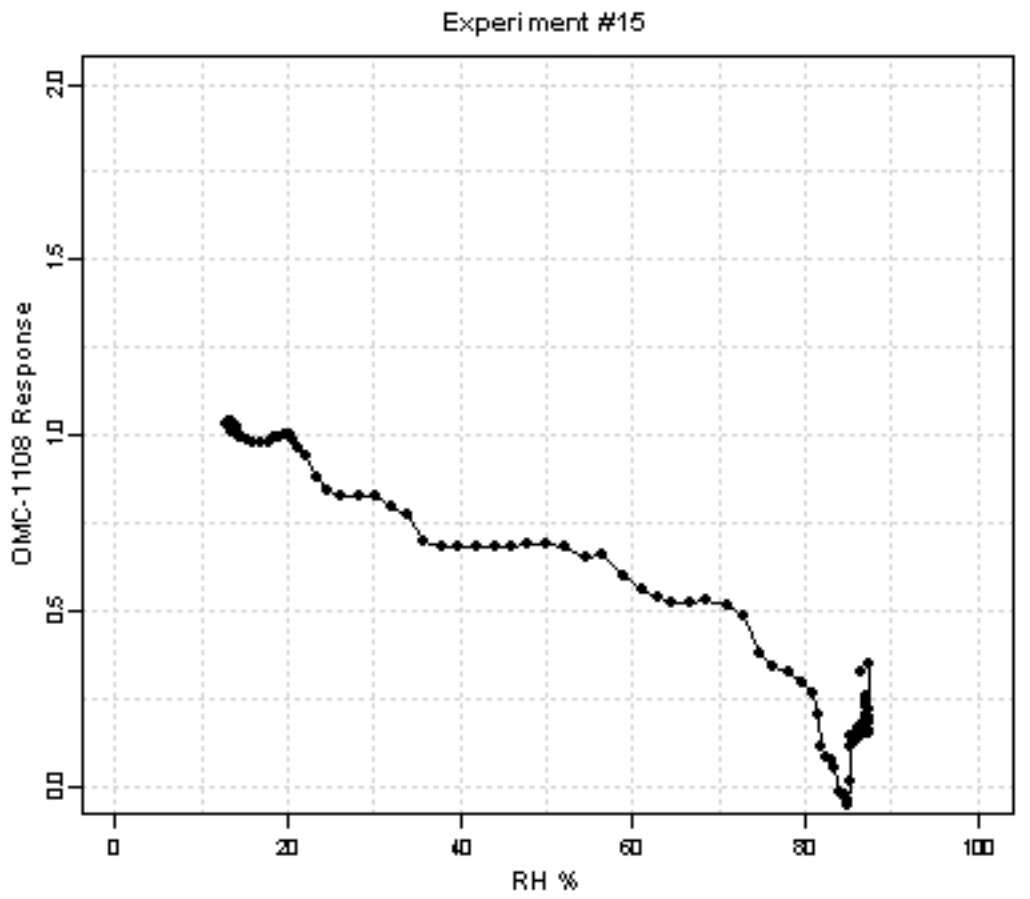
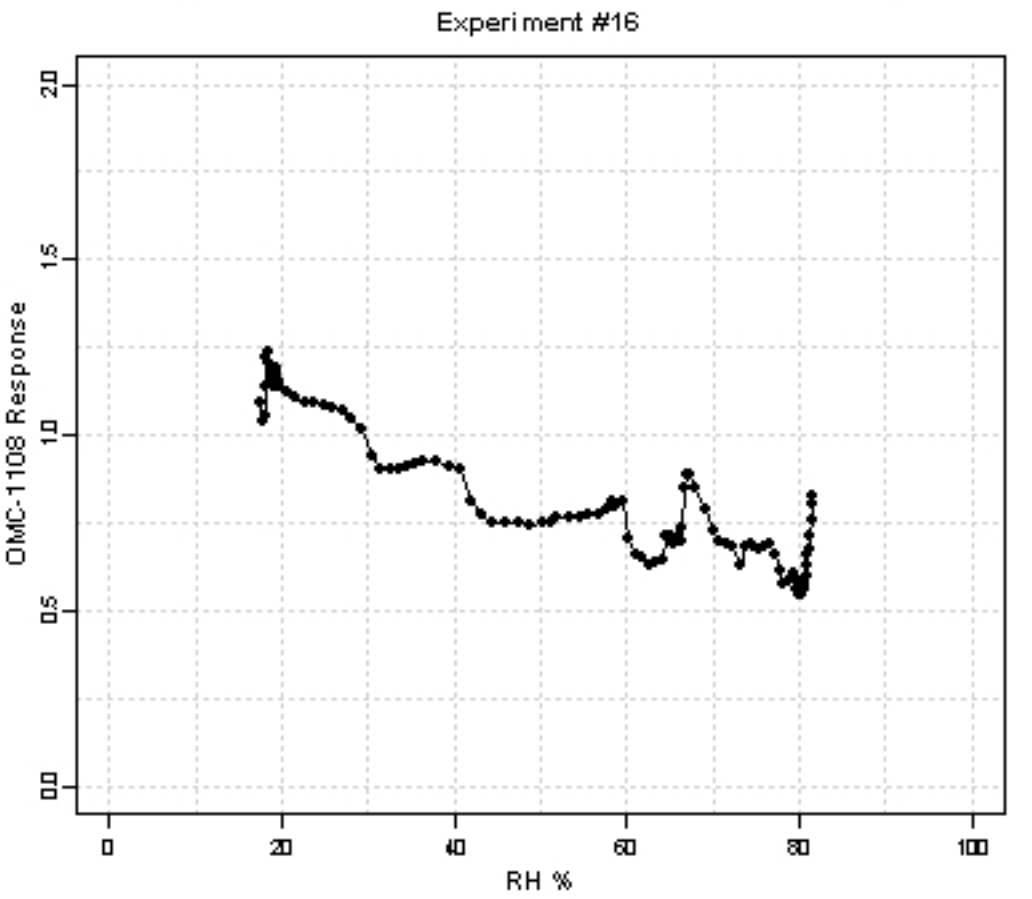
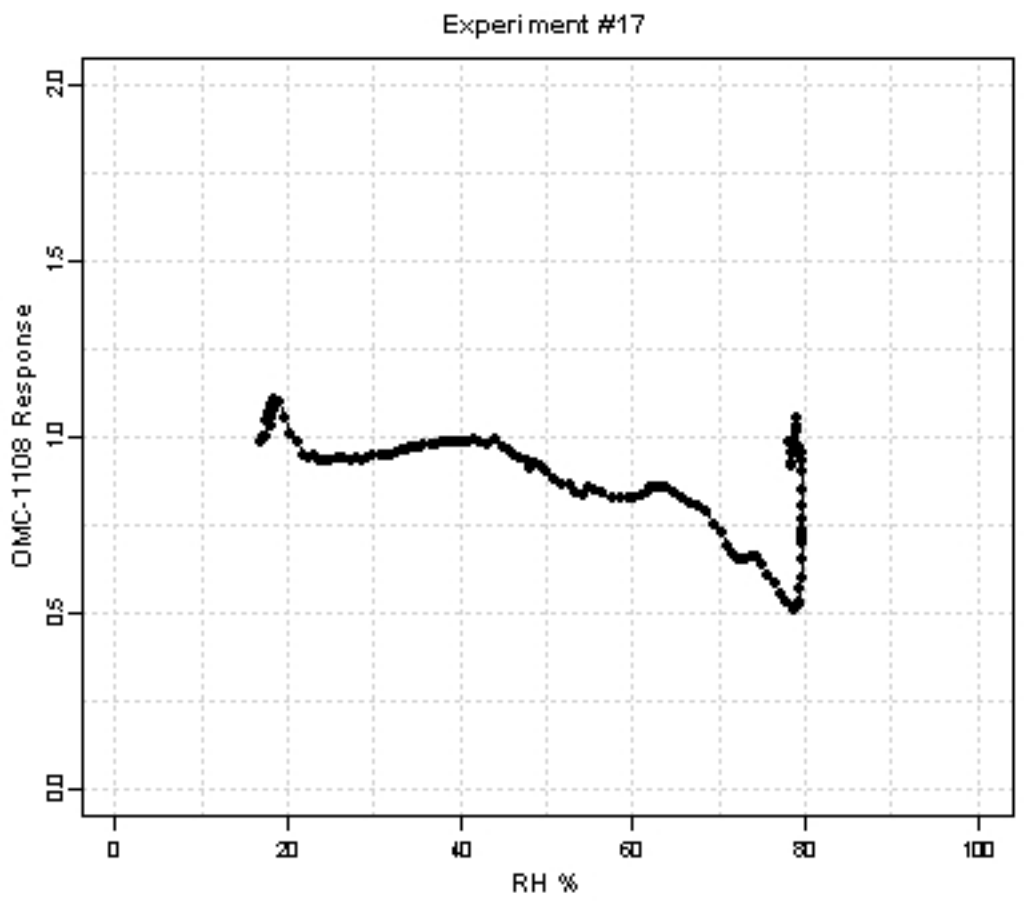
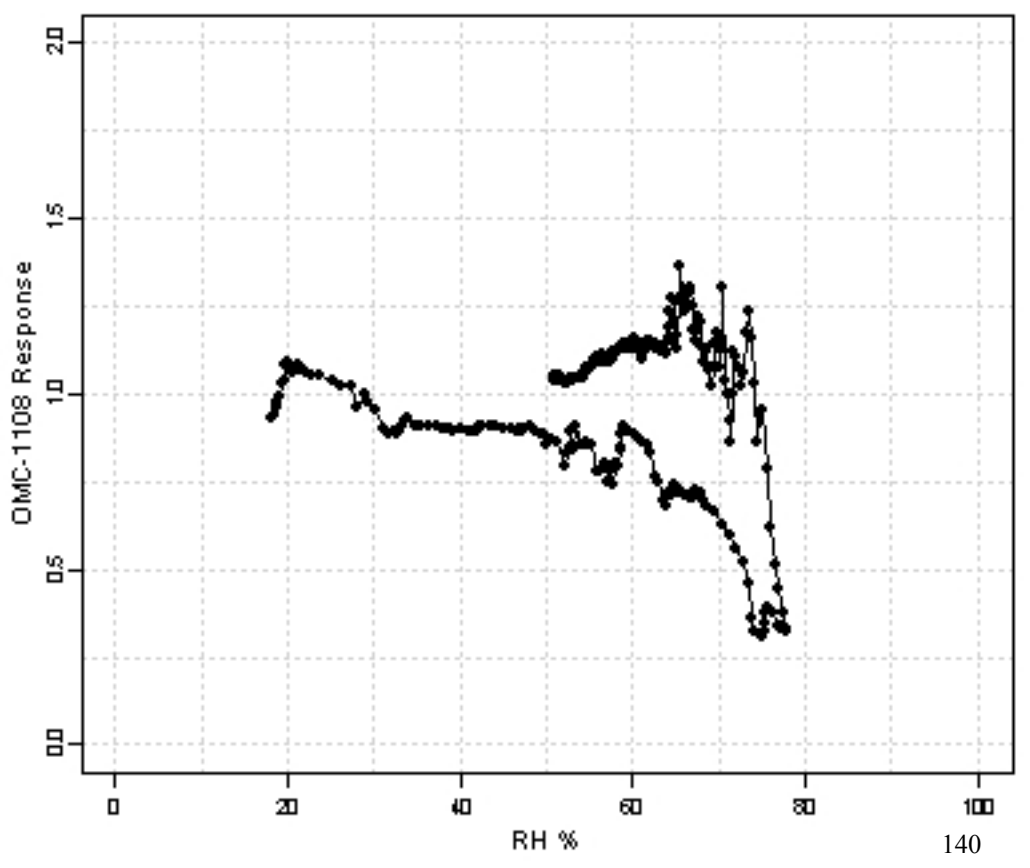


Fig. D20 Ozone Tests: Variable Relative Humidity: OMC-1108/API (Expts 15-20)









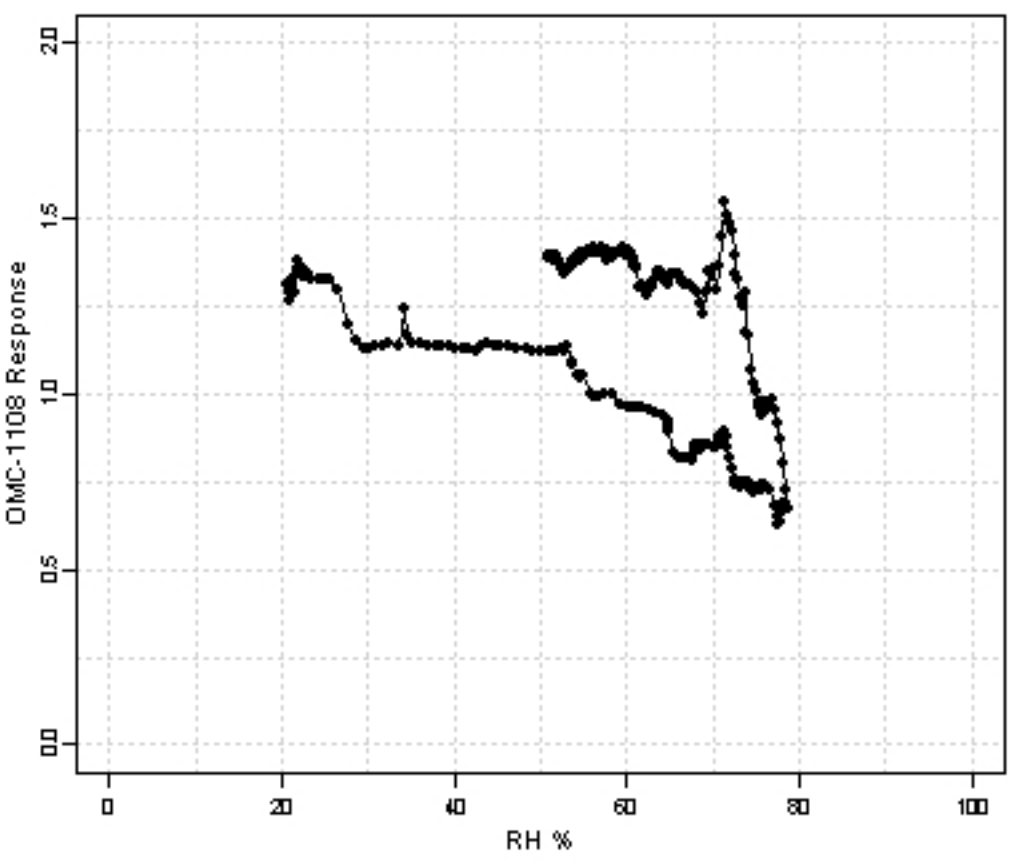
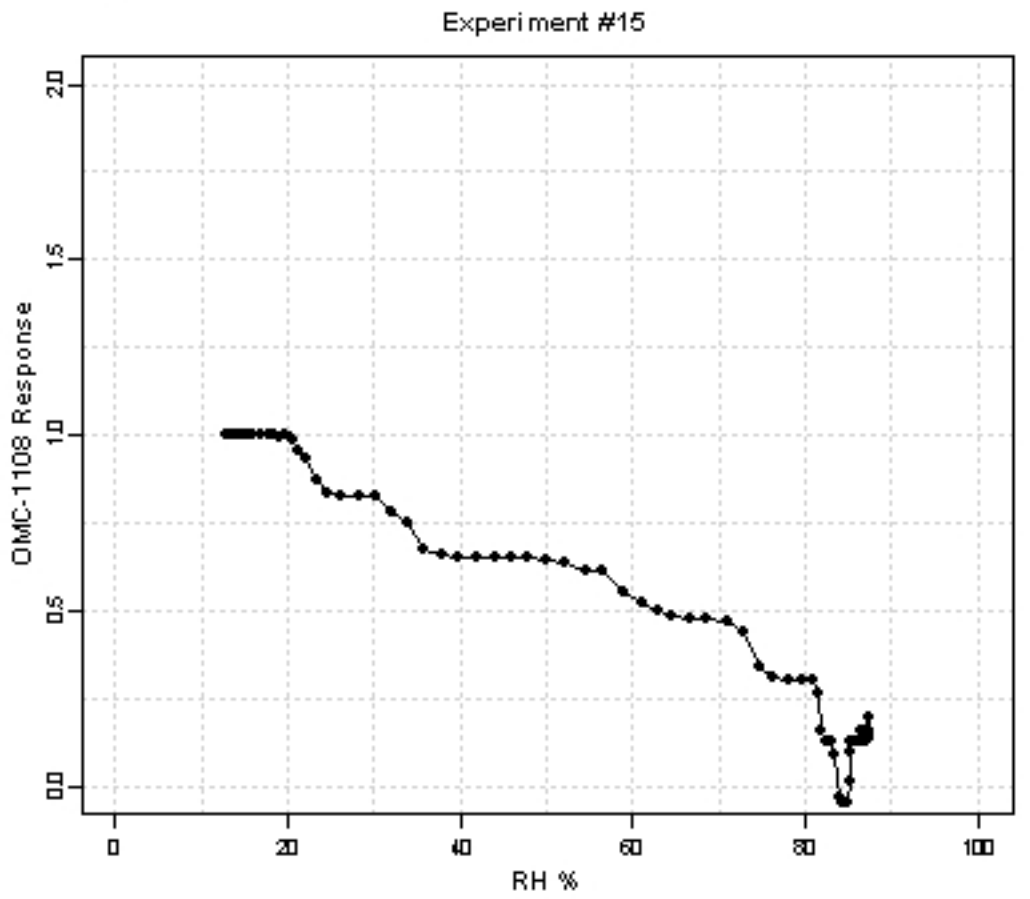
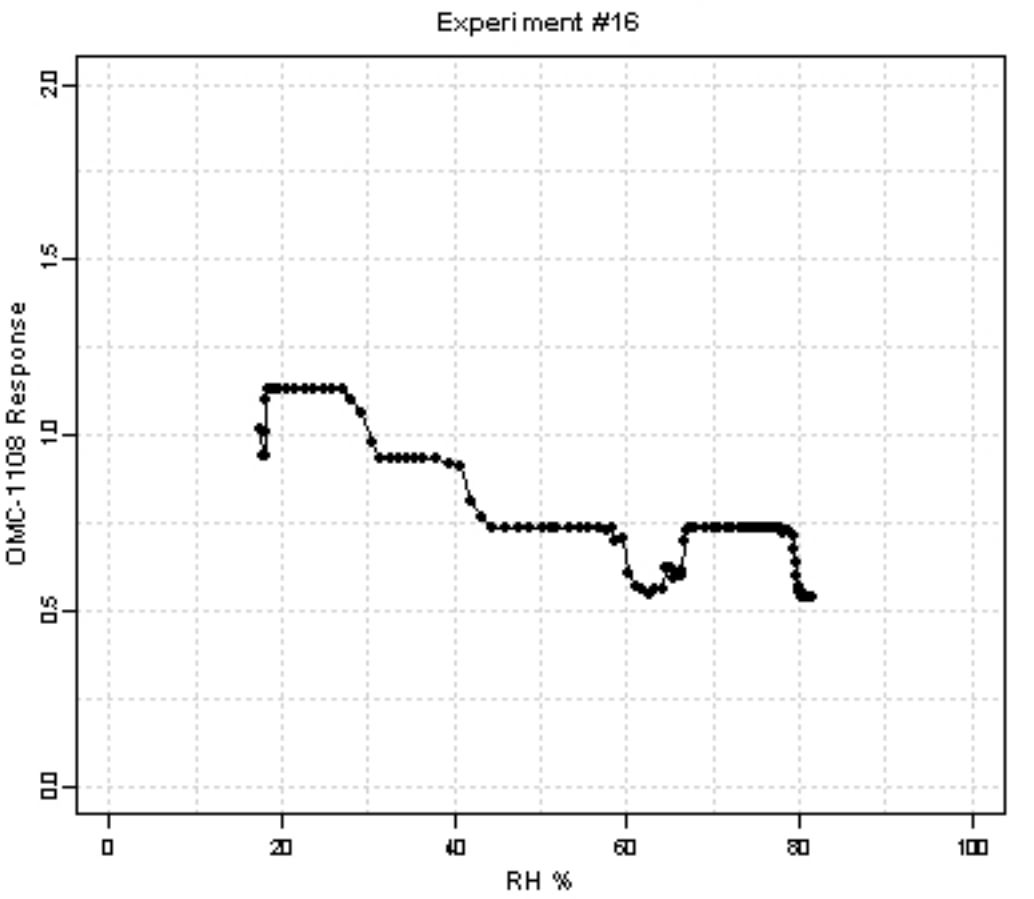
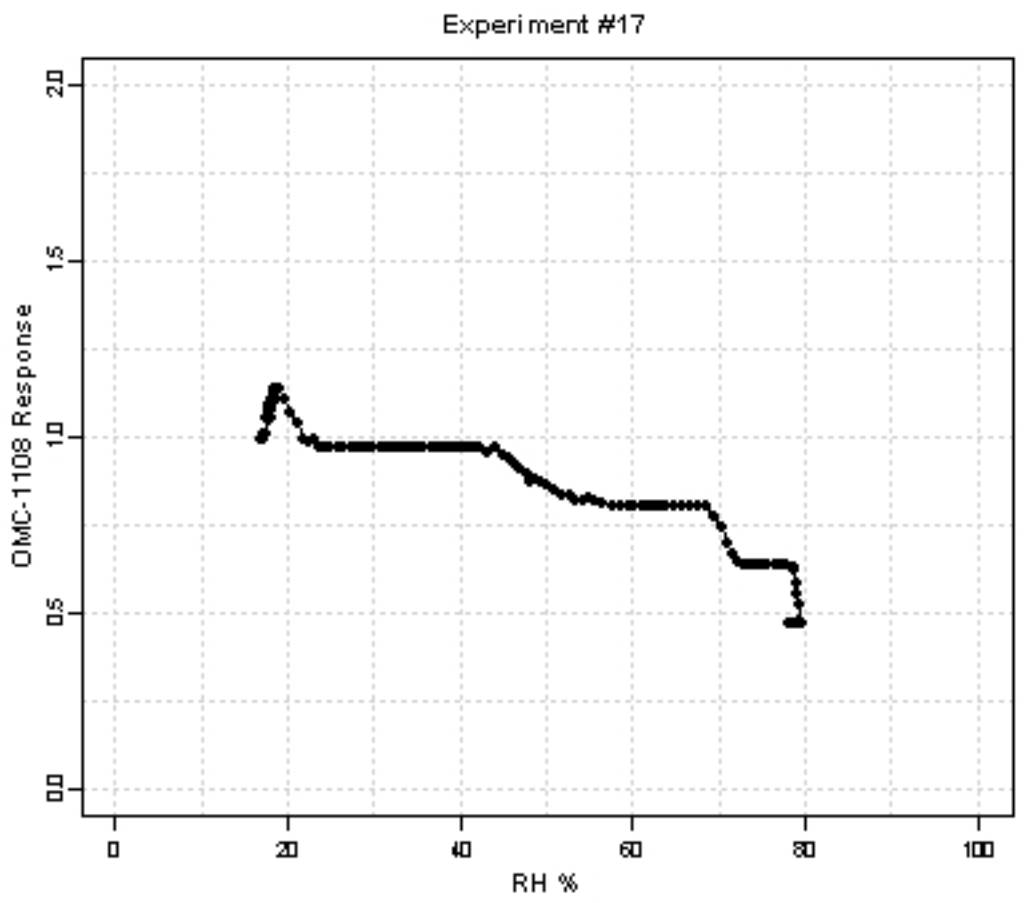
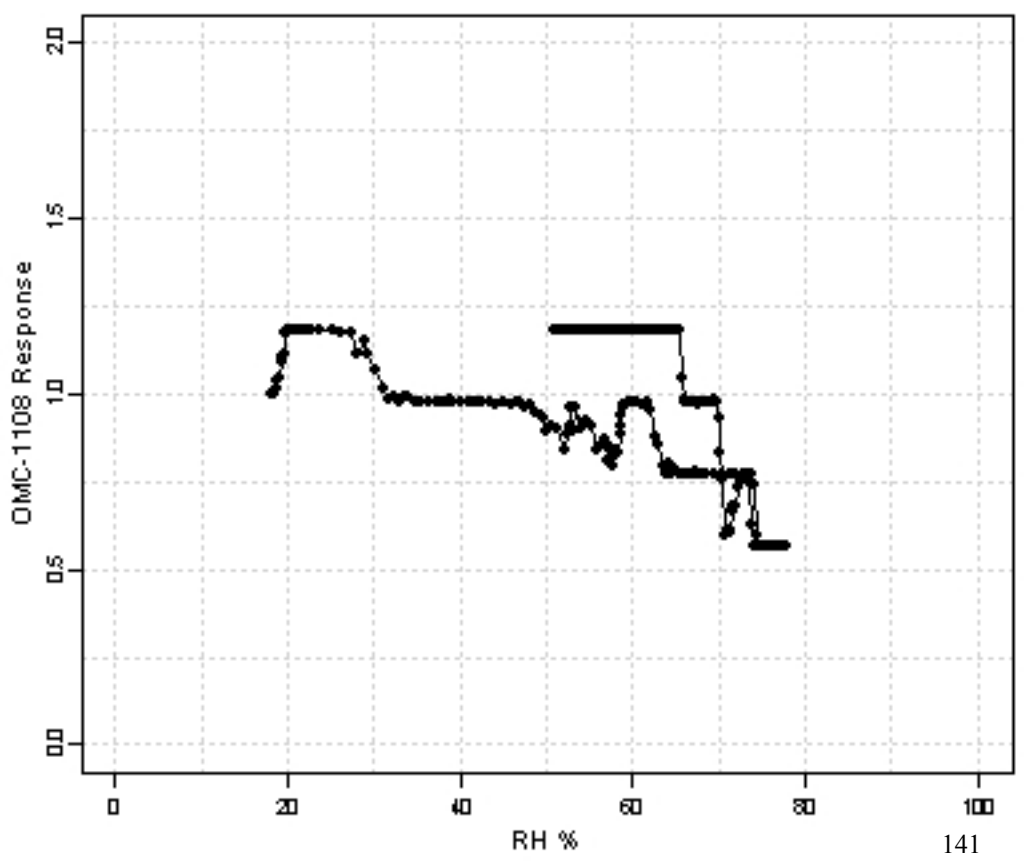


Fig. D21 Ozone Tests: Variable Relative Humidity: OMC-1108/OMC-1108 (Expts 15-20)









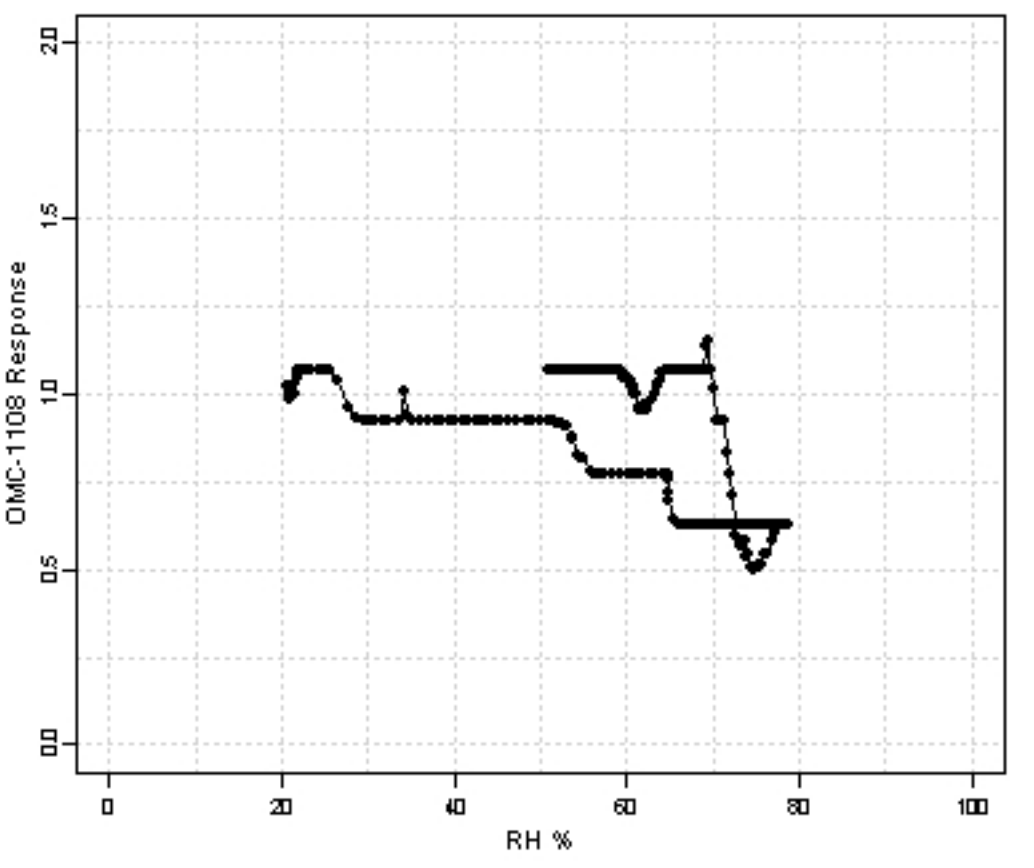
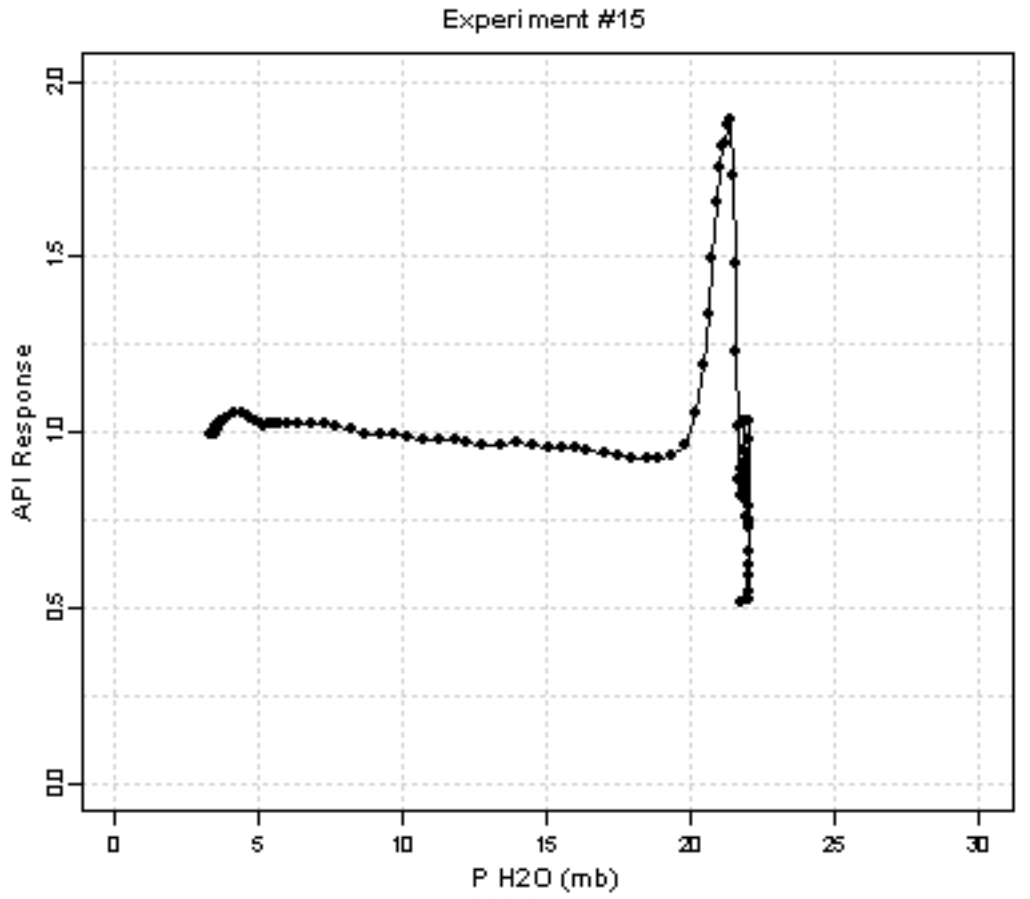
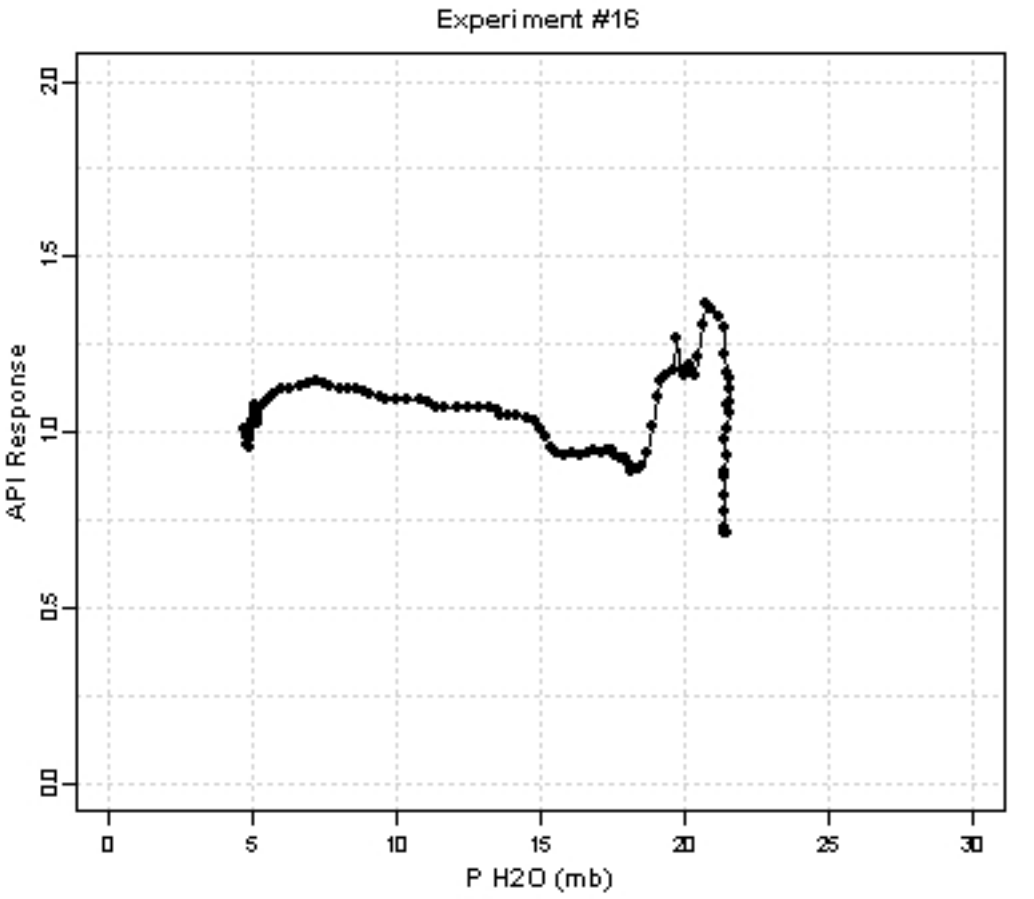
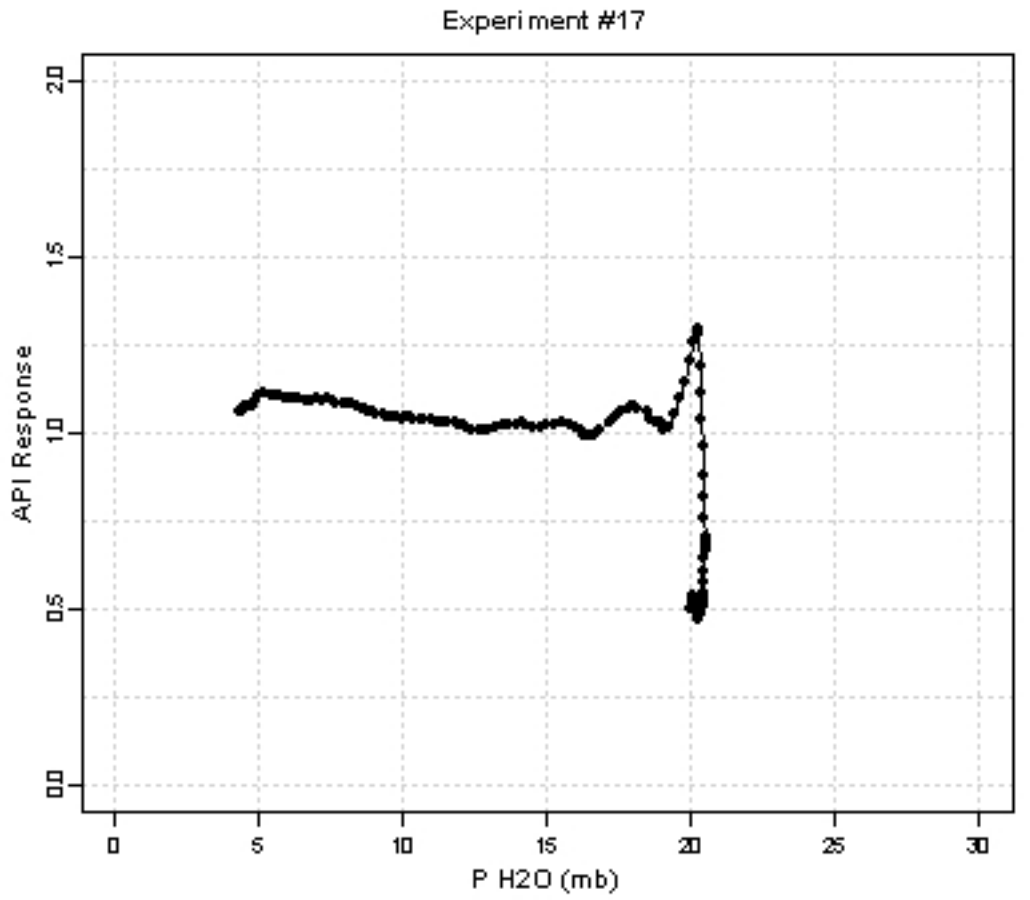
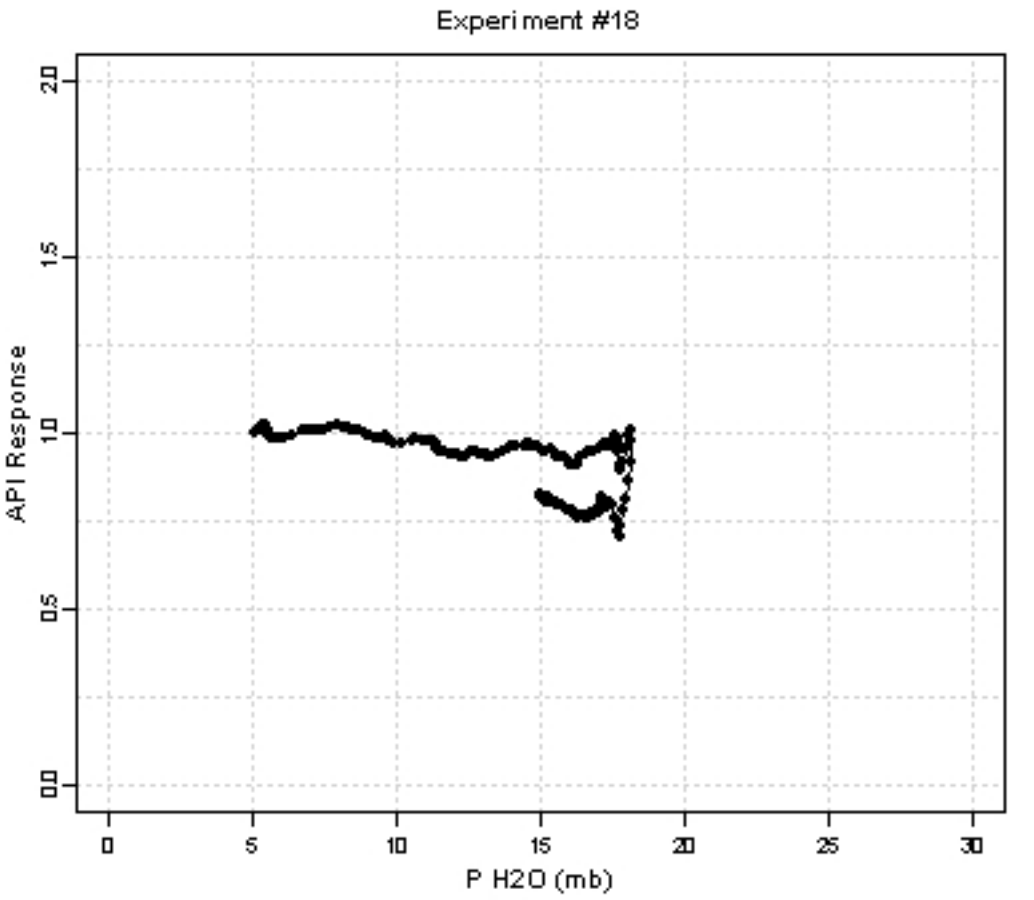


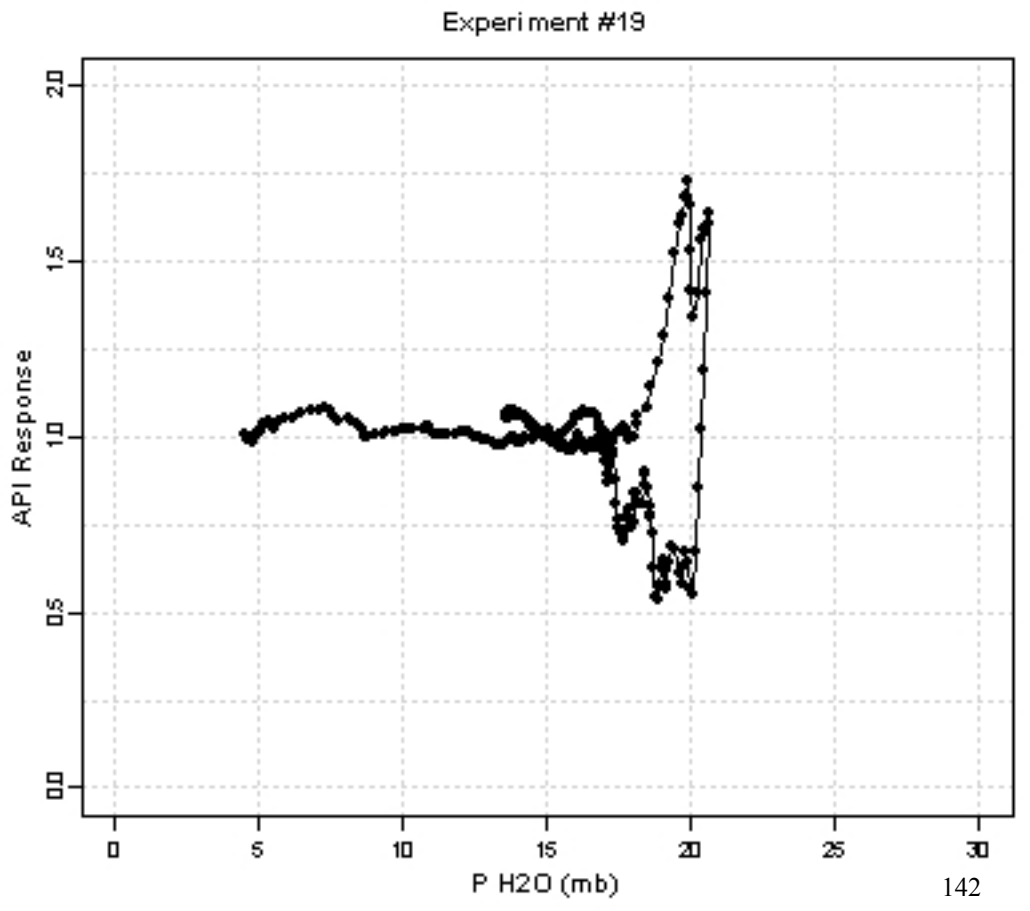
Fig. D22 Ozone Tests: Variable Water Vapor Pressure: API/API (Expts 15-20)











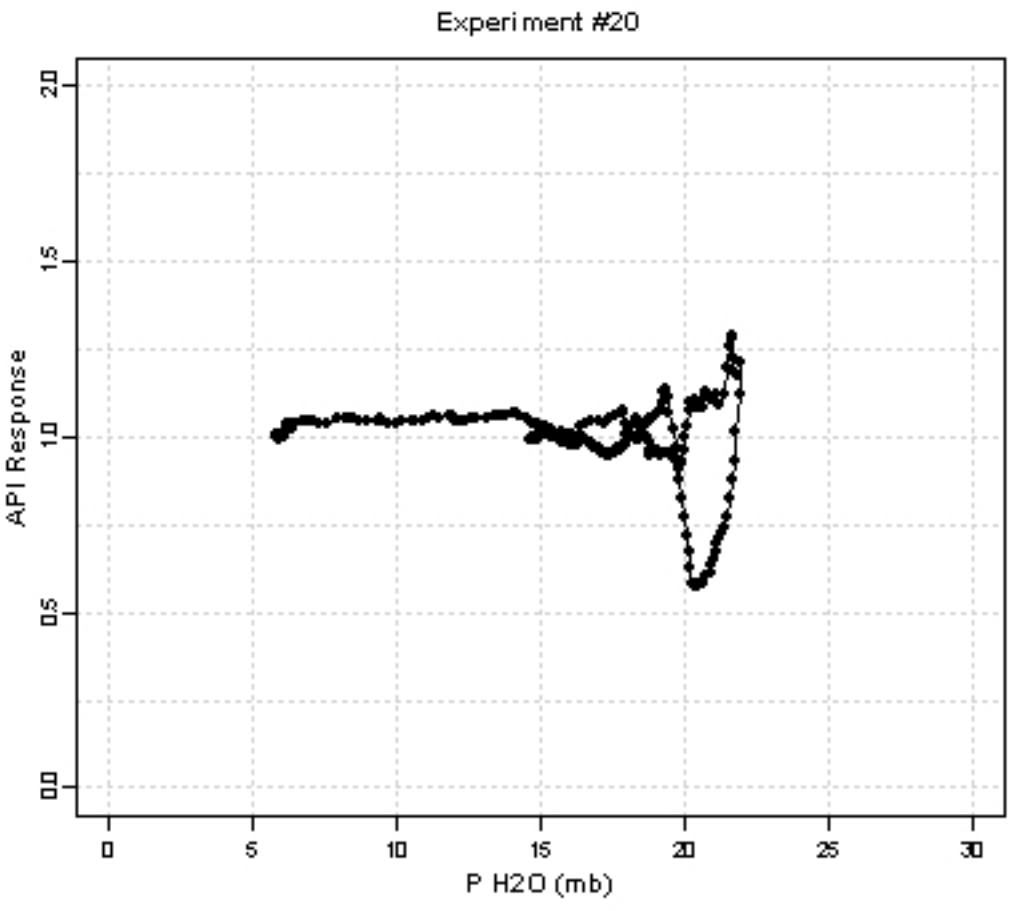
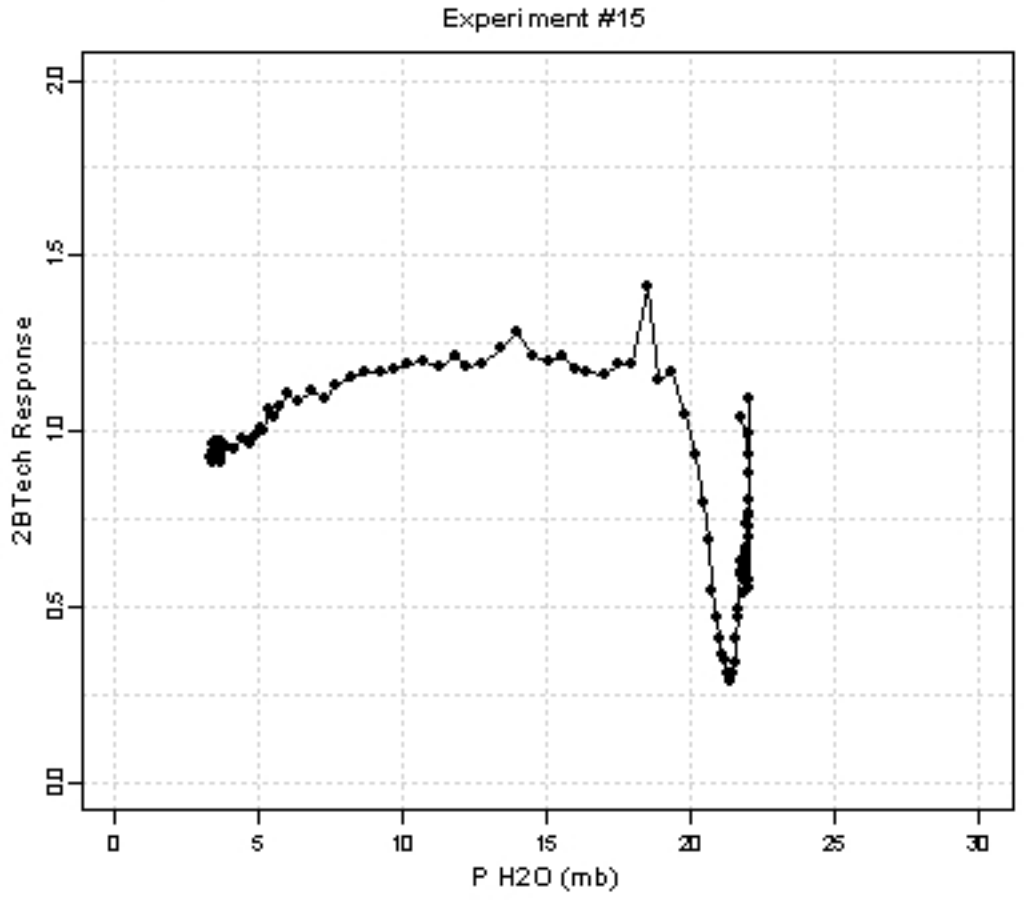
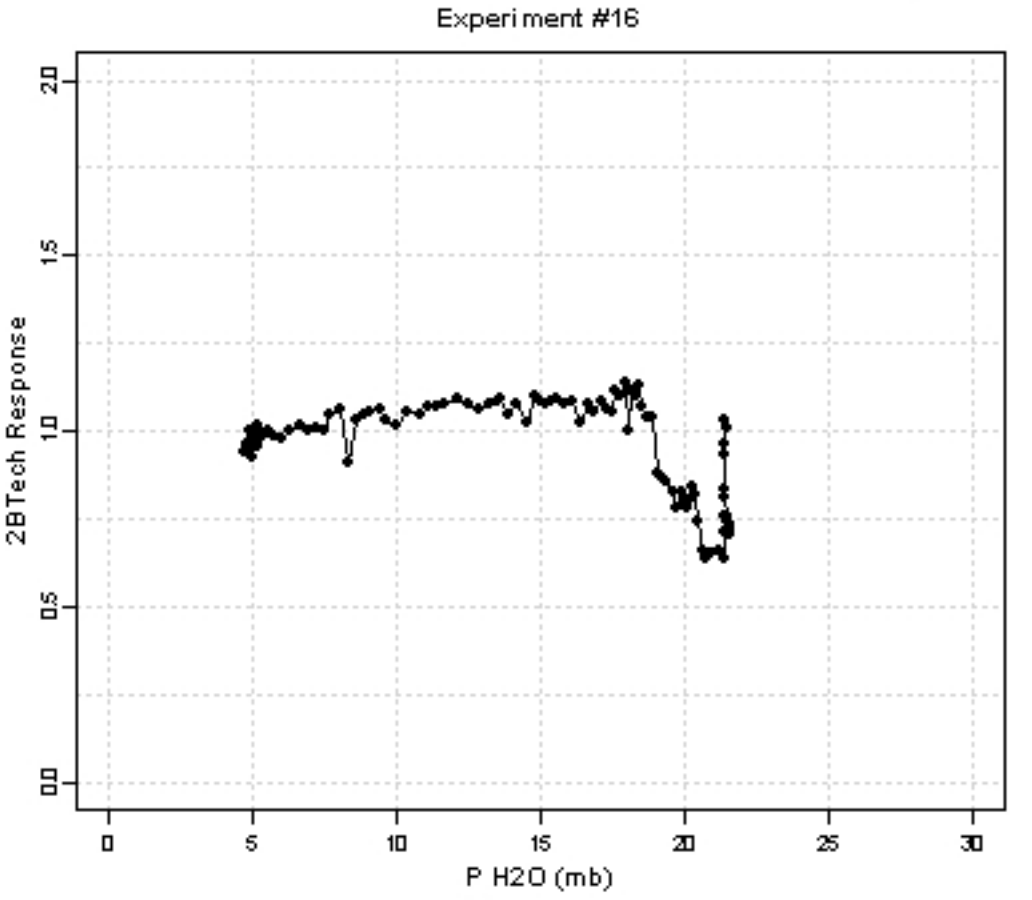
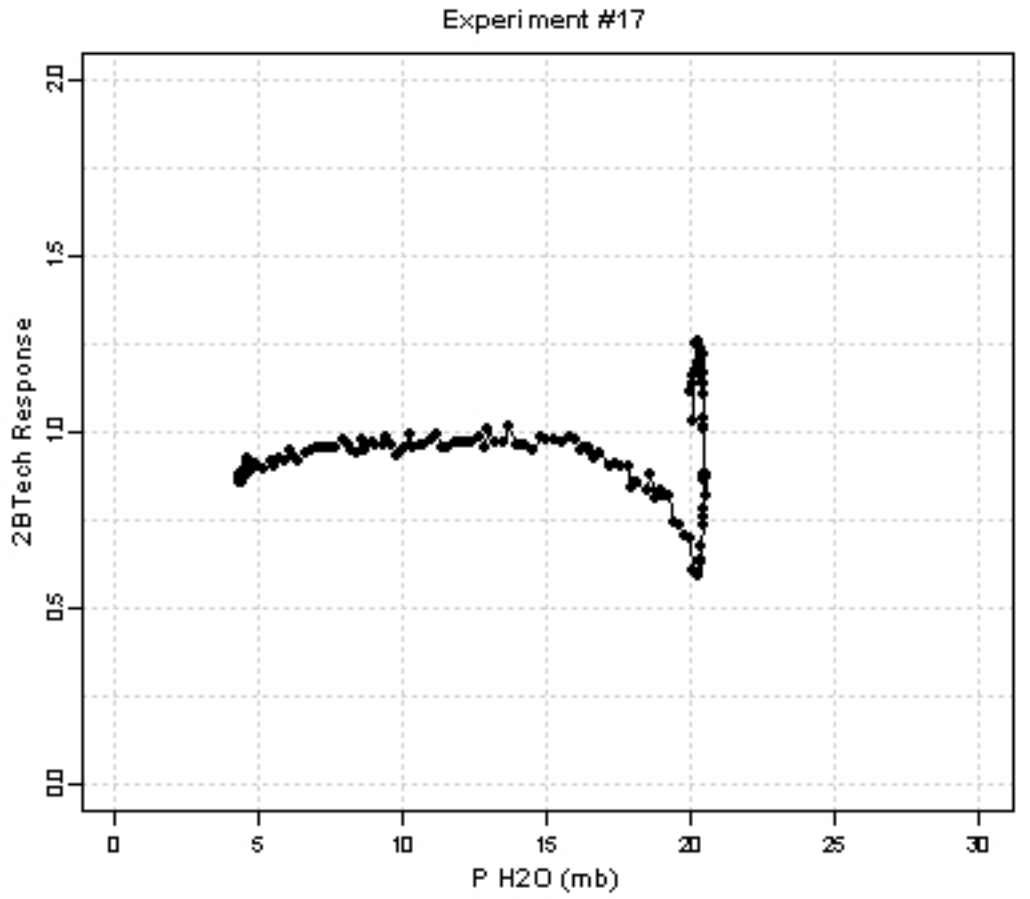
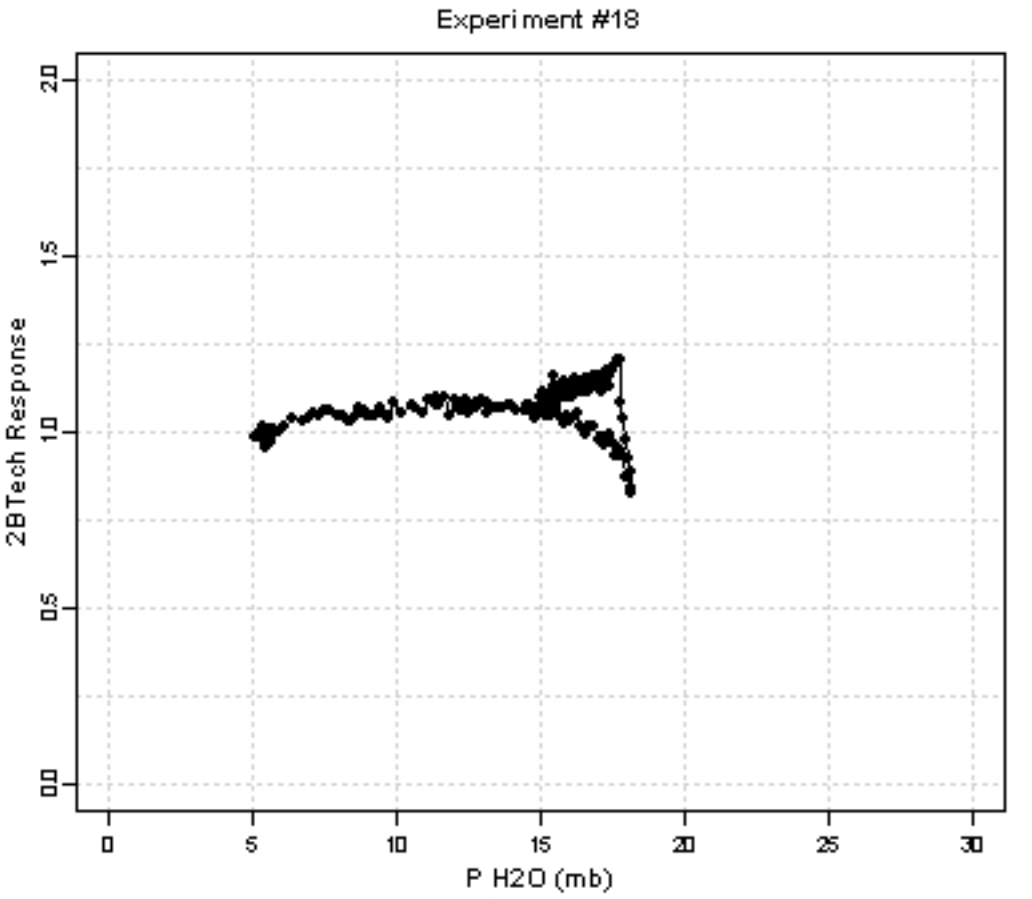


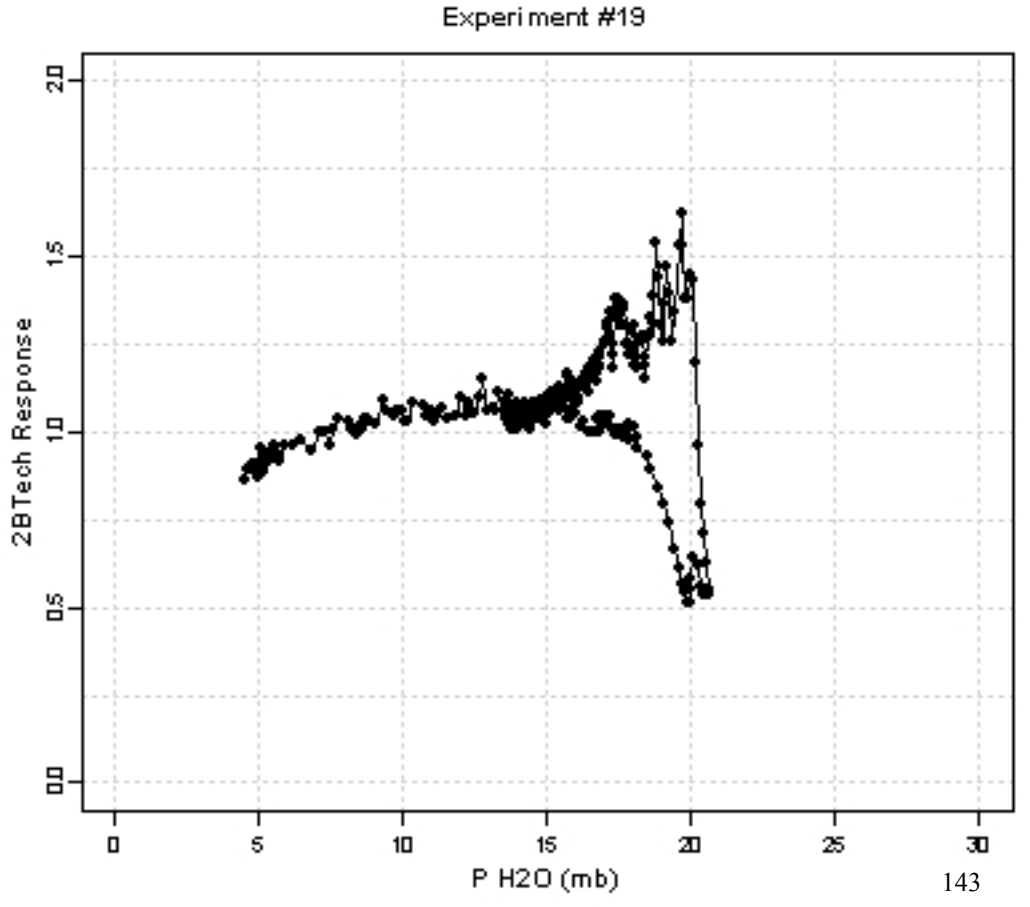
Fig. D23 Ozone Tests: Variable Water Vapor Pressure: 2BTech/API (Expts 15-20)











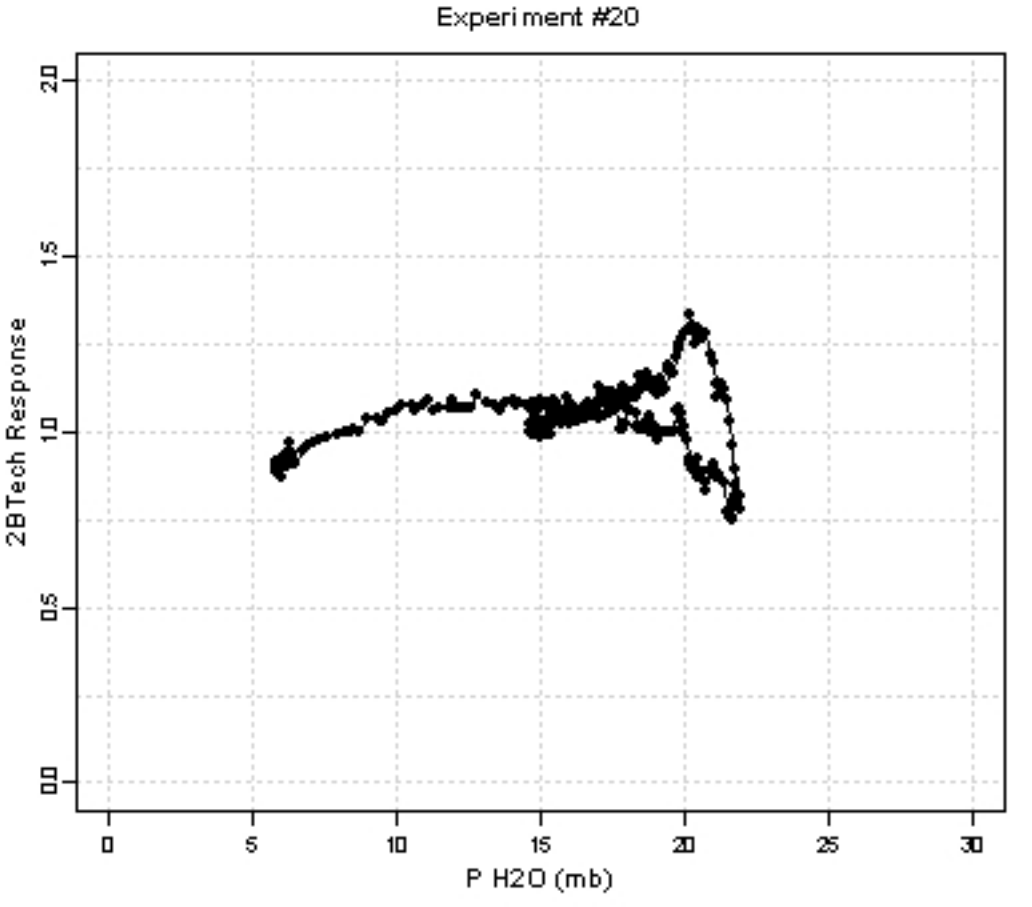
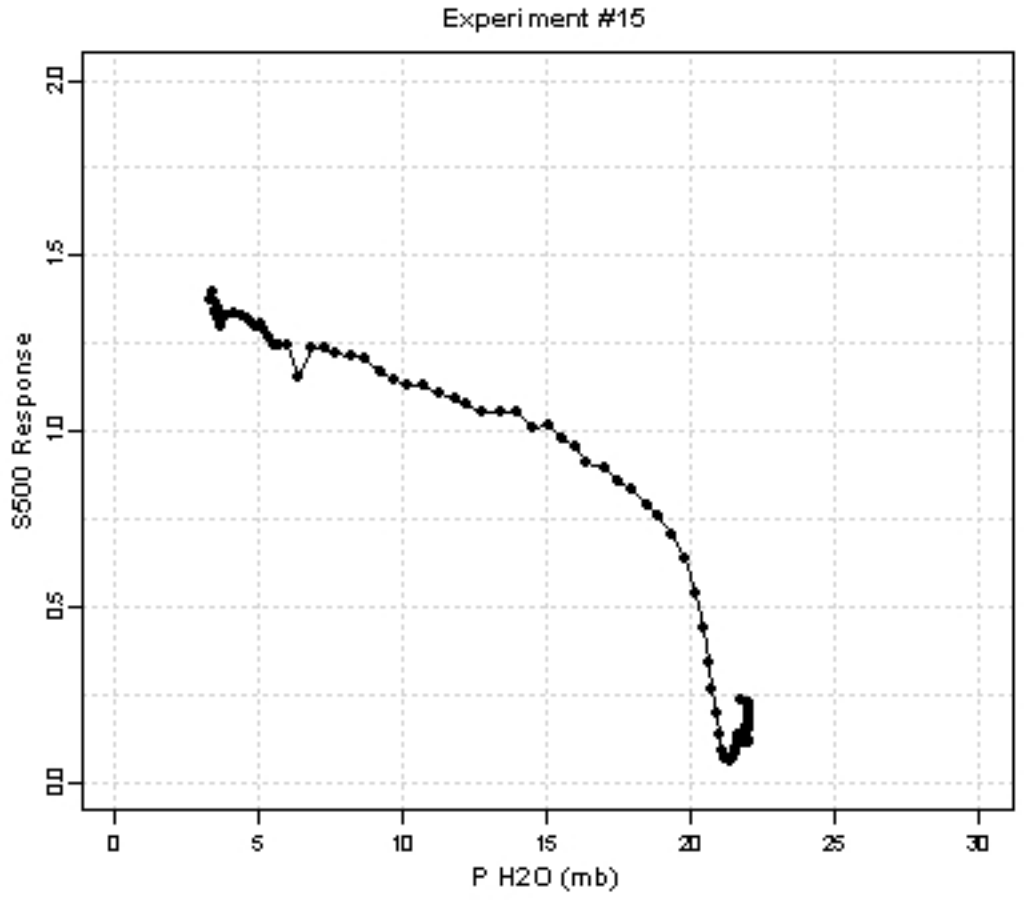
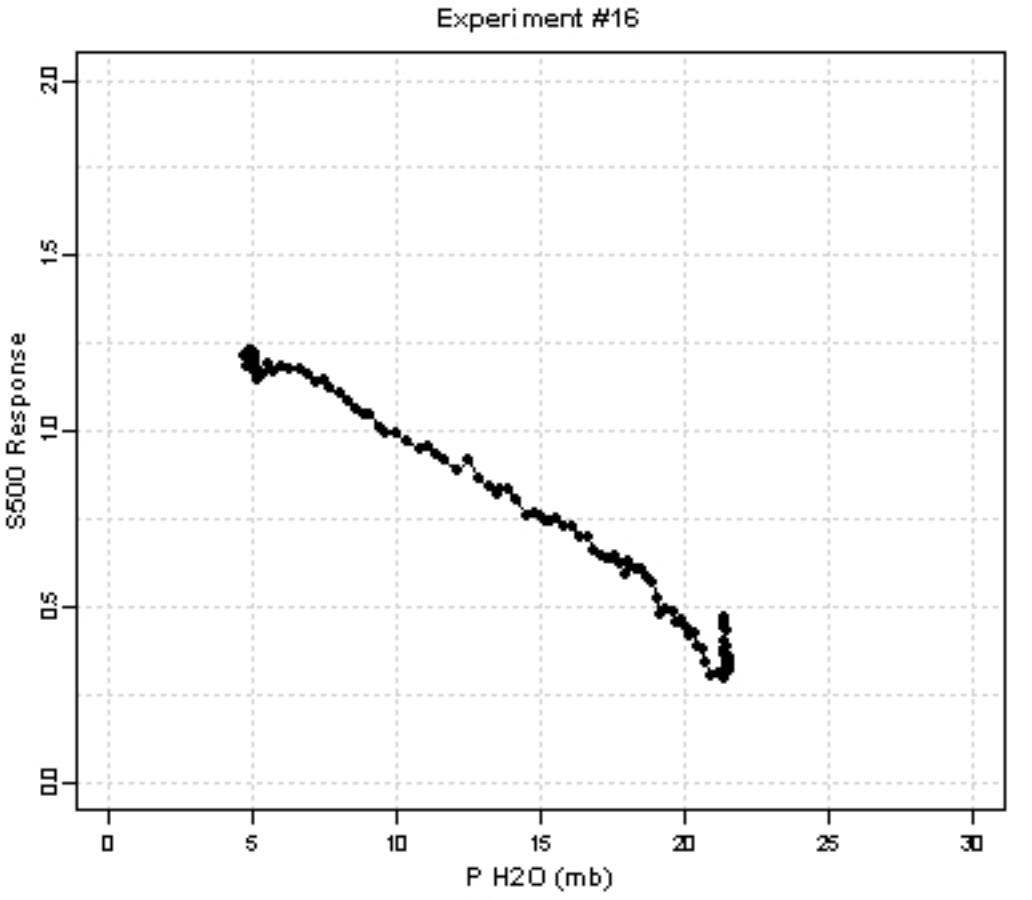
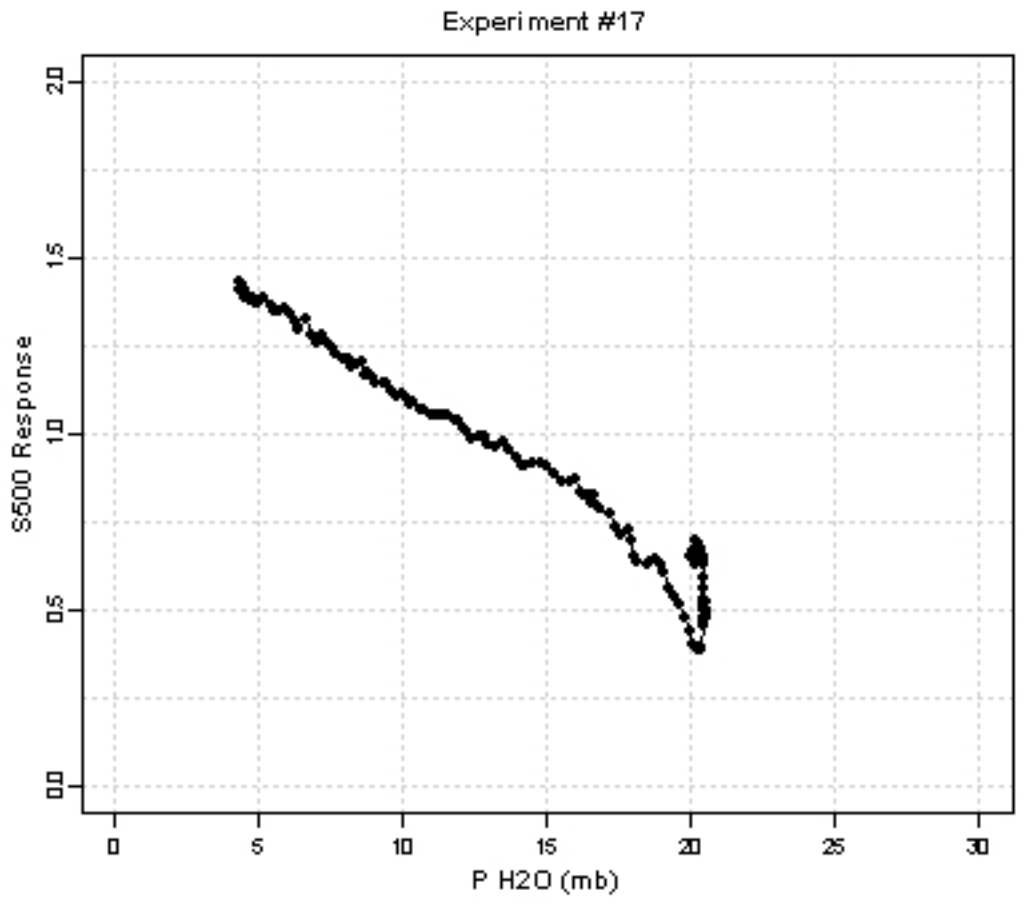
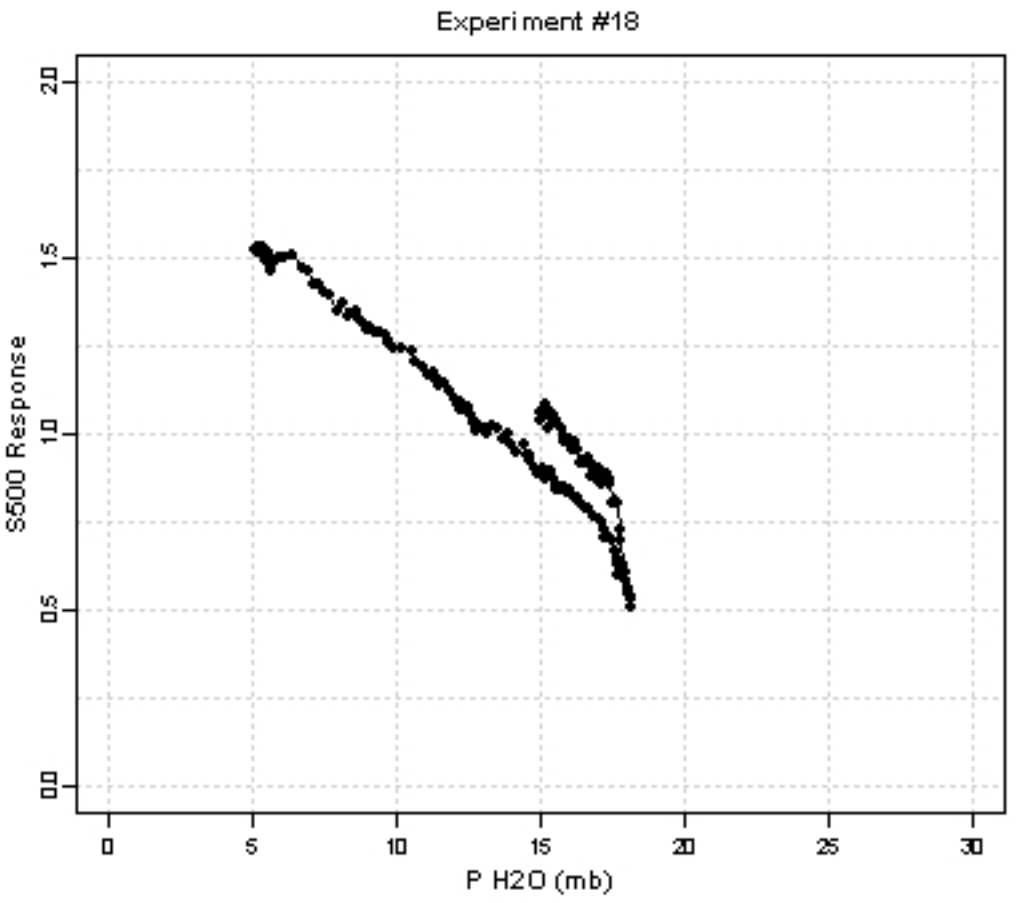


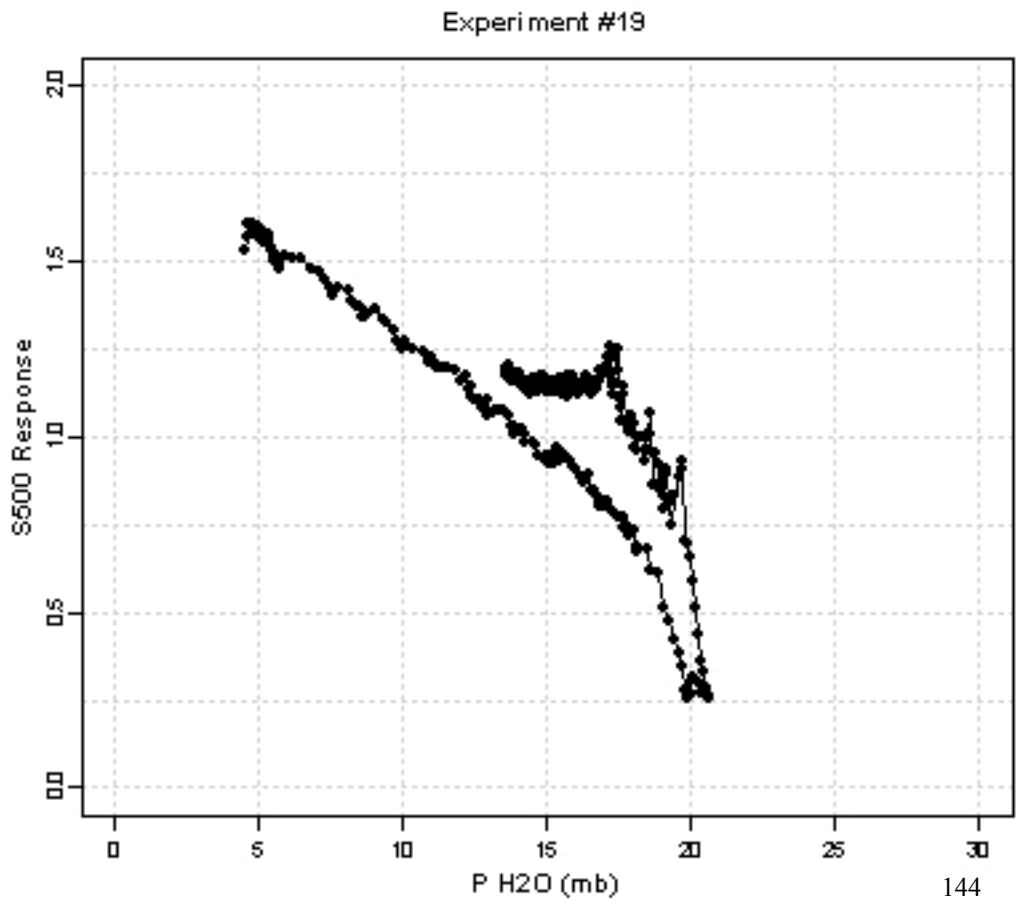
Fig. D24 Ozone Tests: Variable Water Vapor Pressure: S500/API (Expts 15-20)











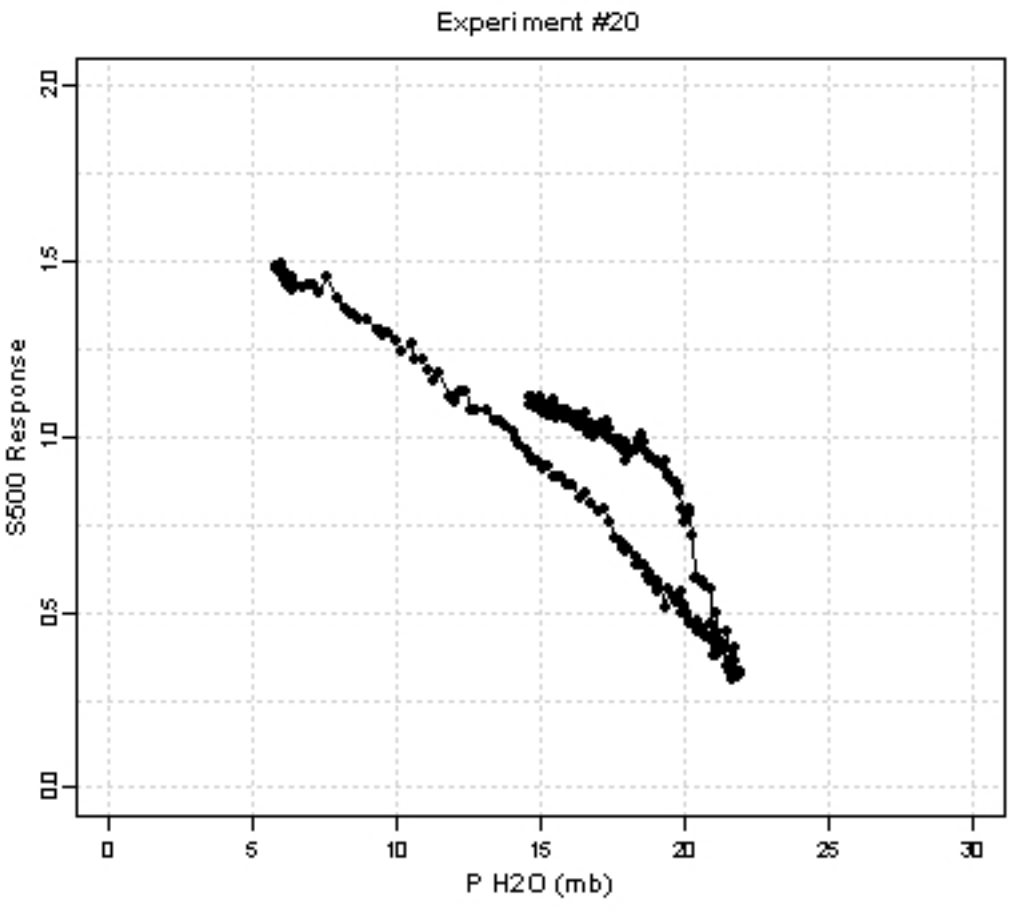
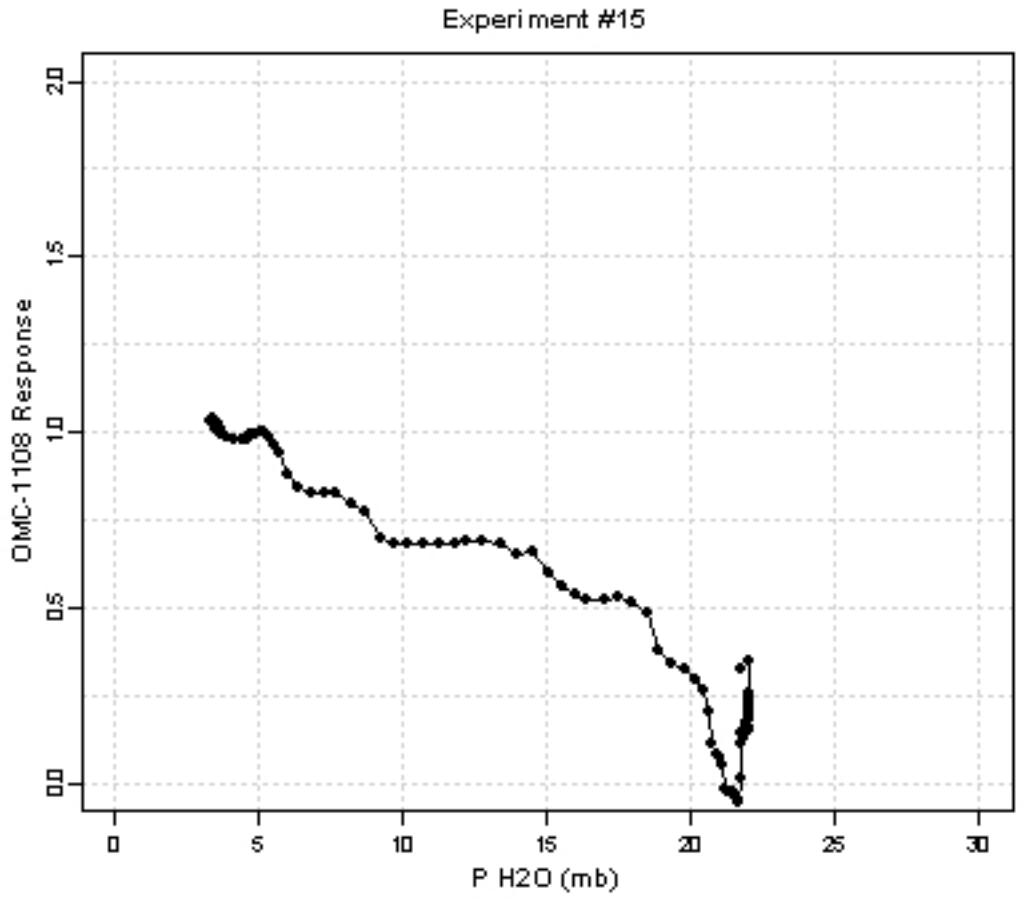
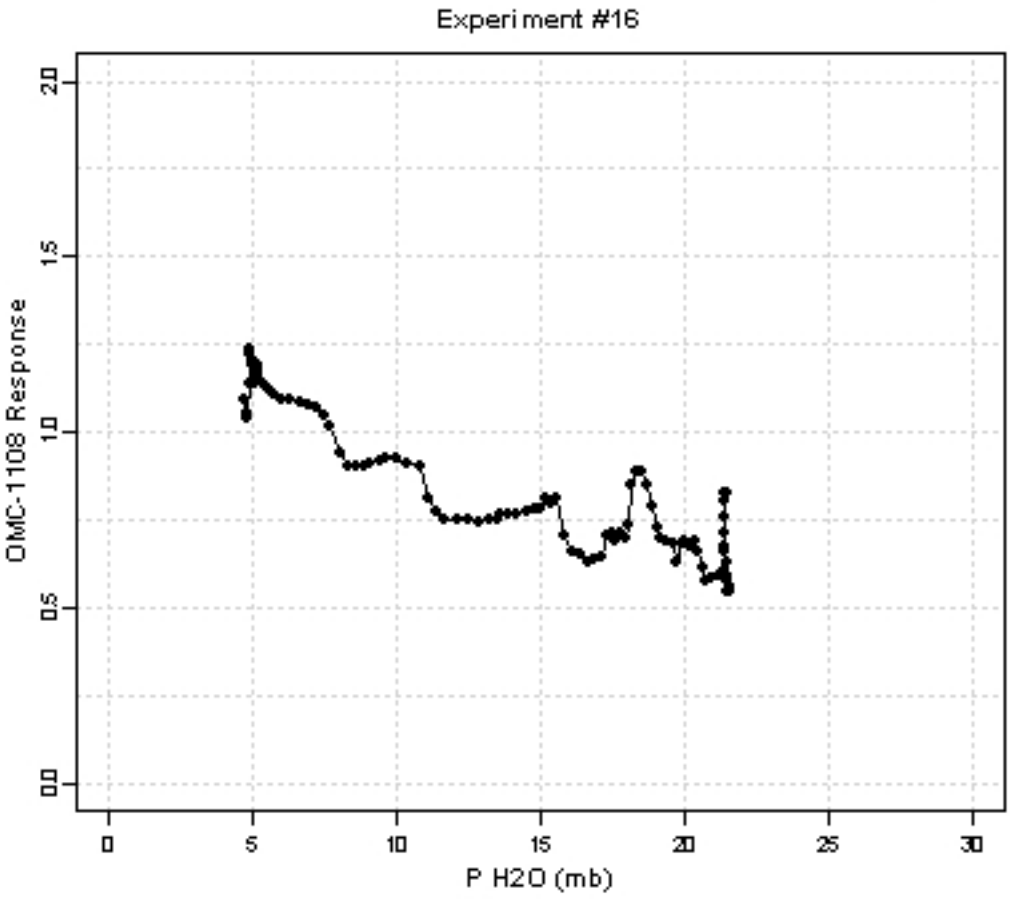
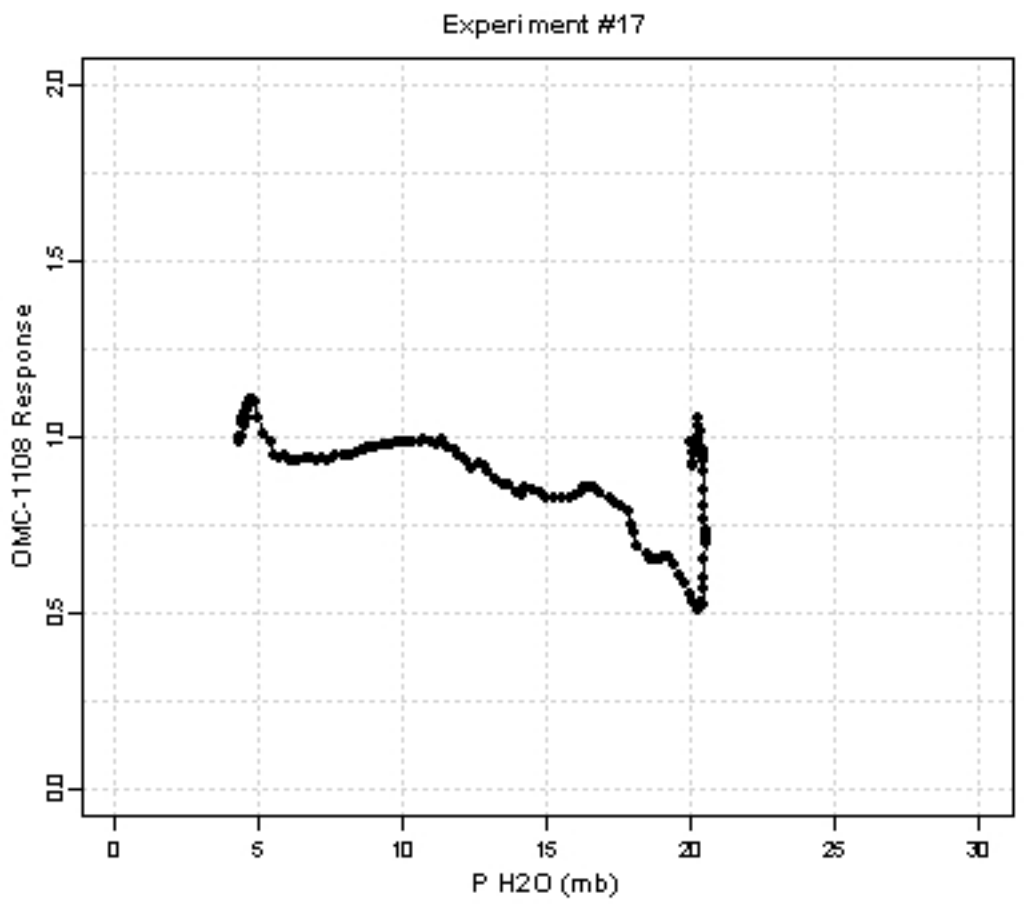
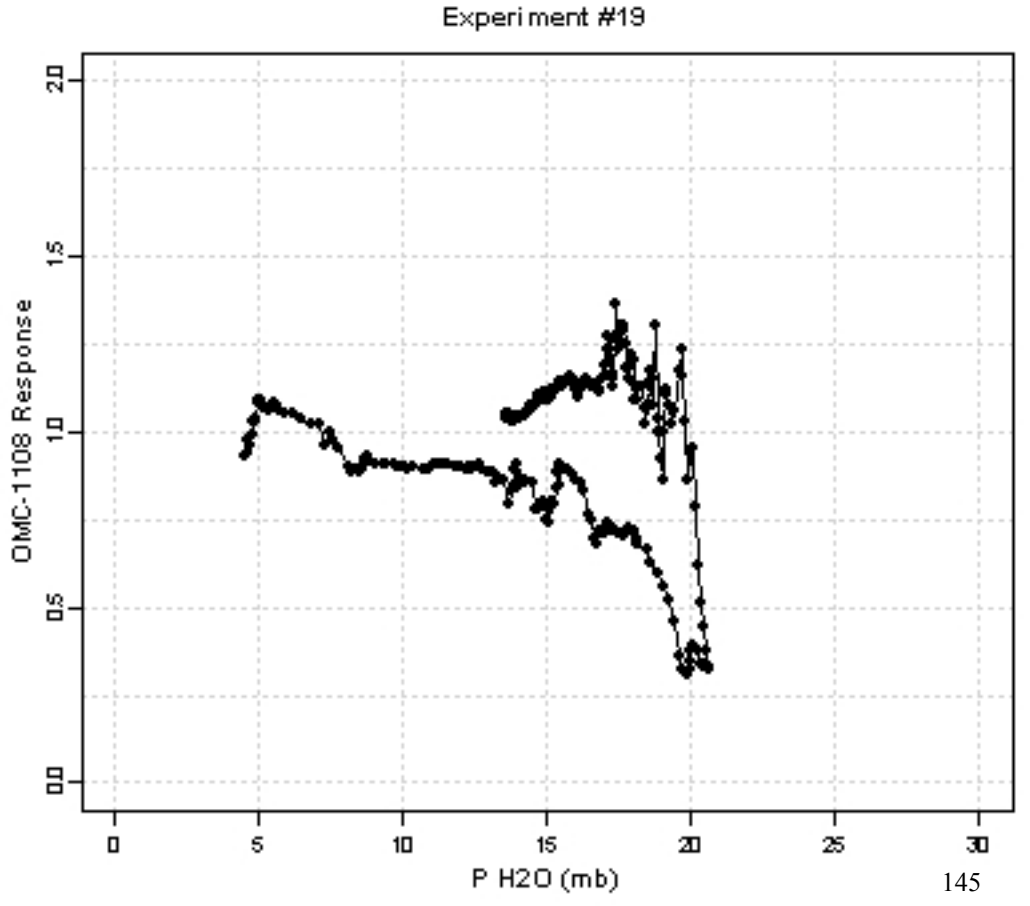


Fig. D25 Ozone Tests: Variable Water Vapor Pressure: OMC-1108/API (Expts 15-20)









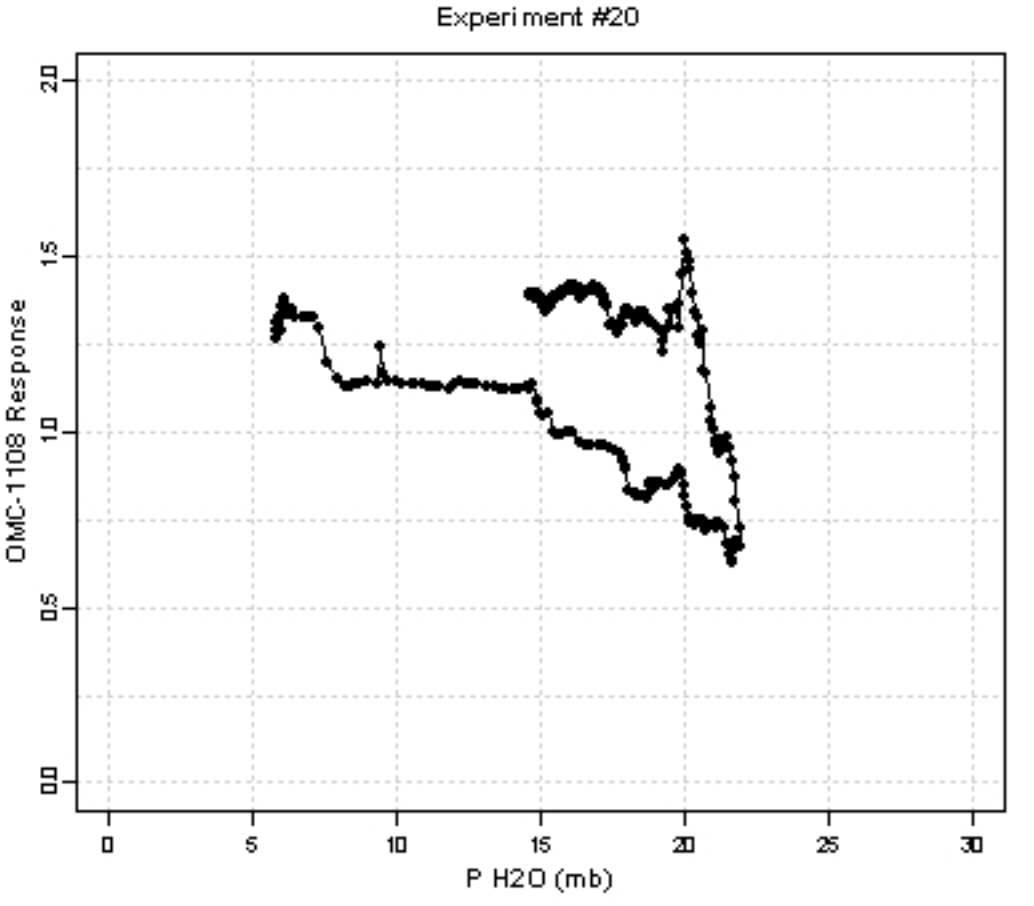
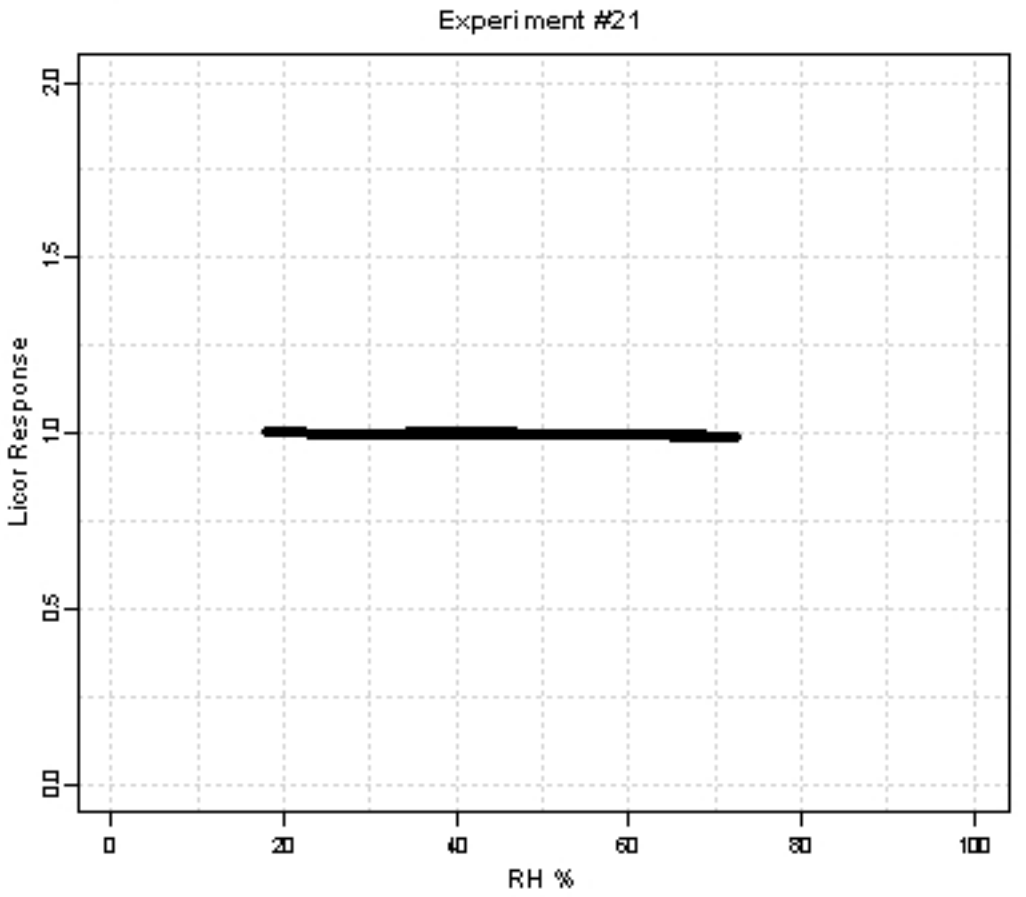
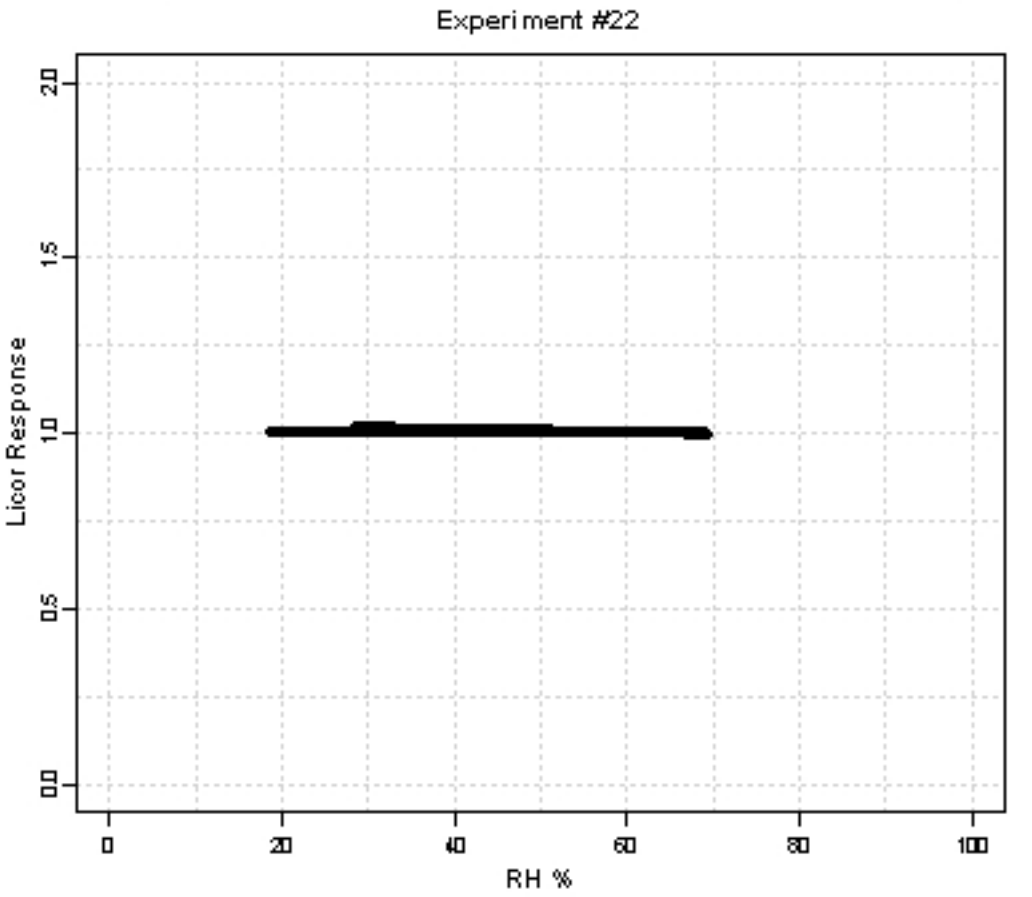
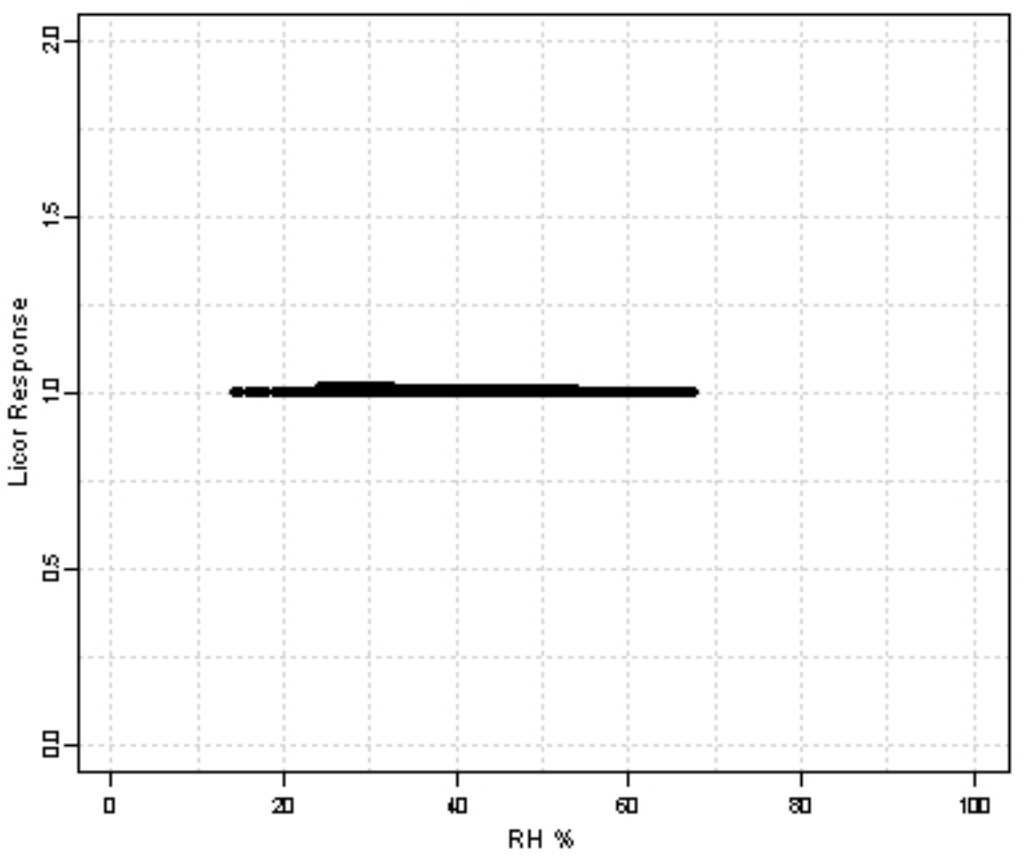


Fig. D26 CO/CO2 Tests: Variable Relative Humidity #2: Licor/Licor CO2 (Expts 21-24)







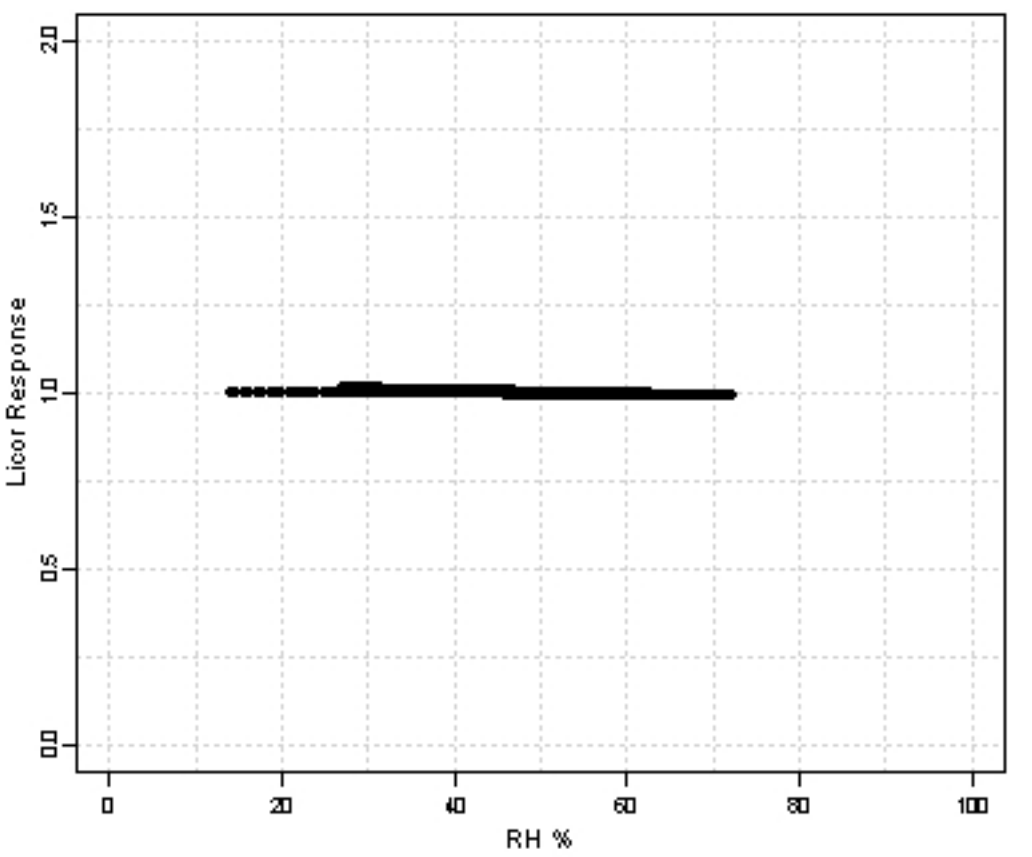
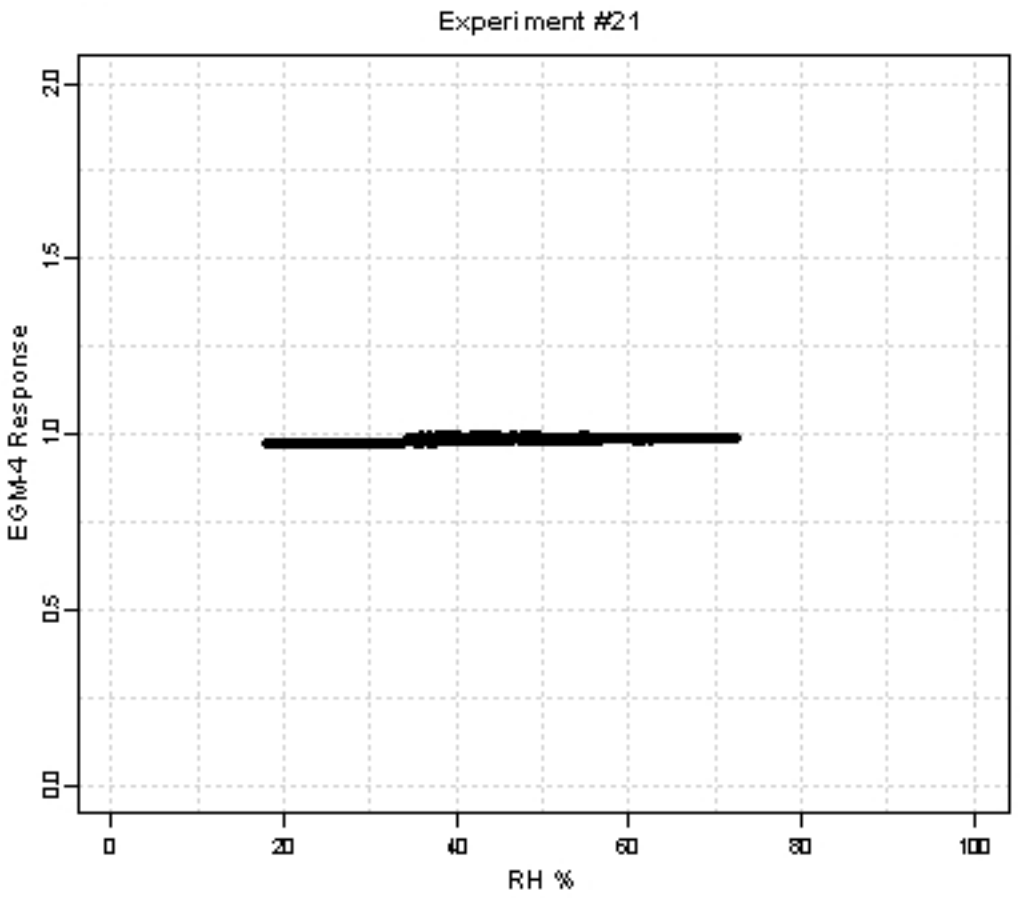
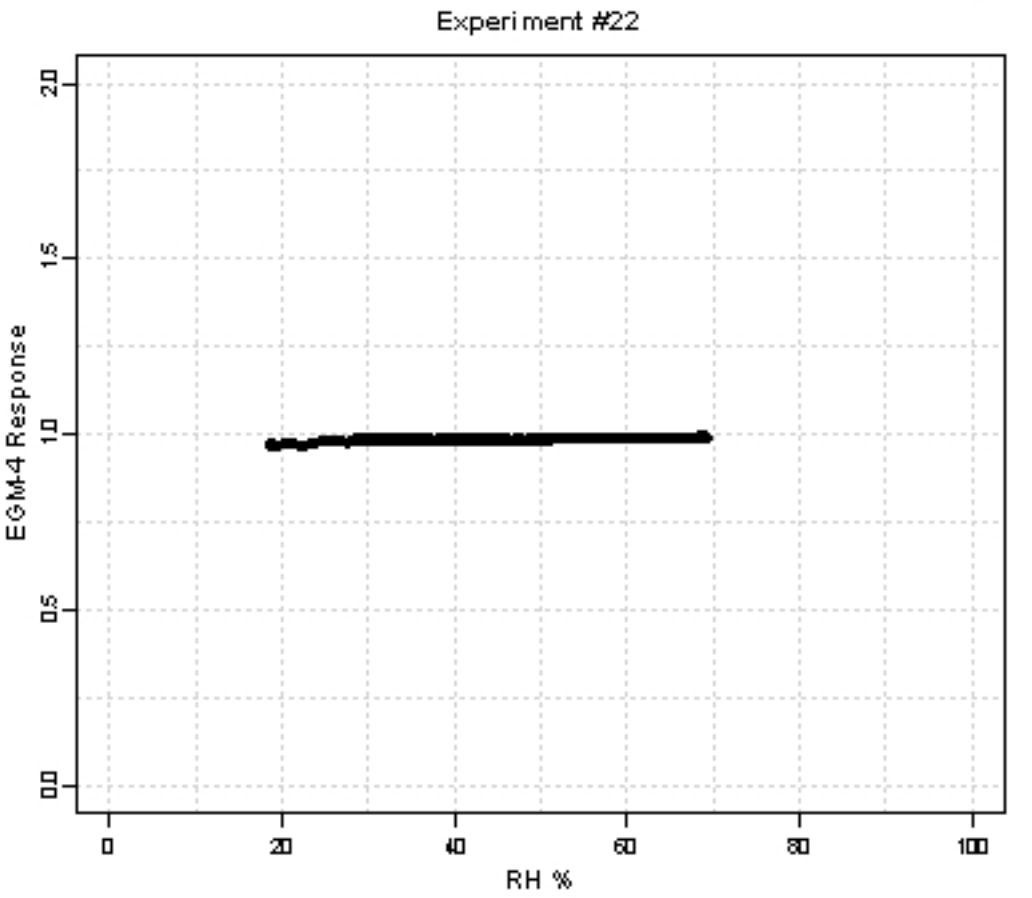
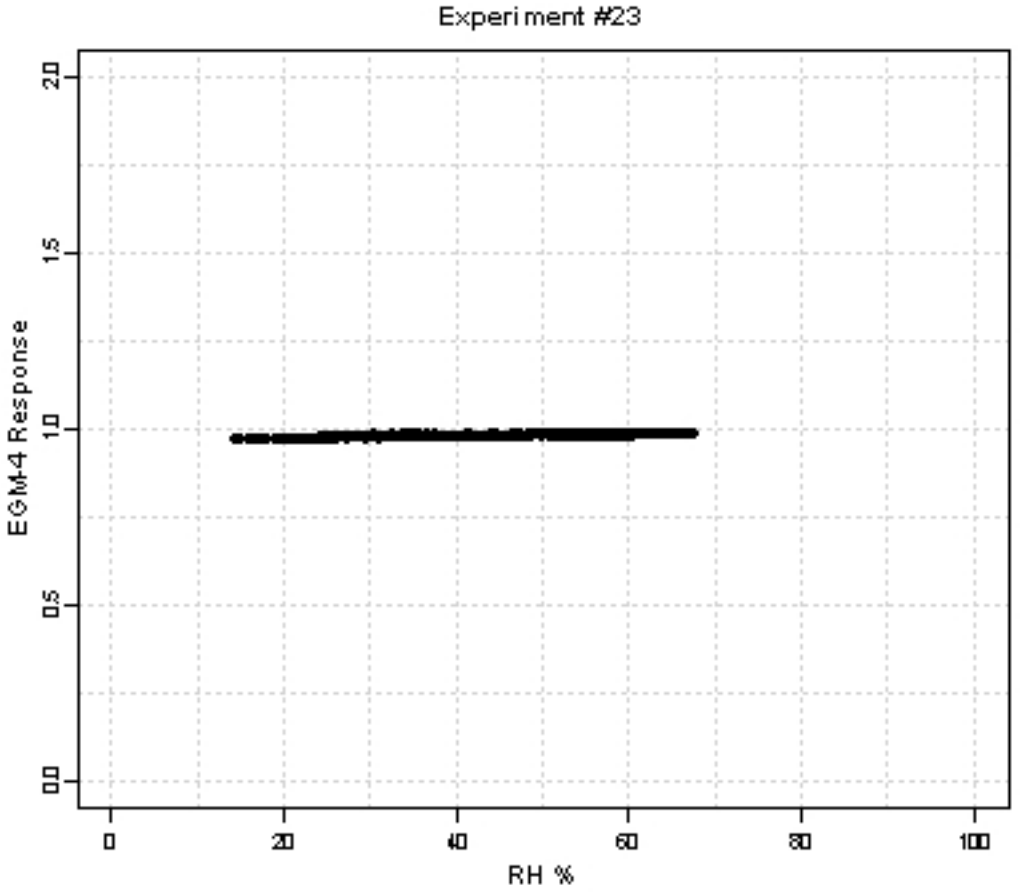


Fig. D27 CO/CO2 Tests: Variable Relative Humidity #2: EGM-4/Licor CO2 (Expts 21-24)







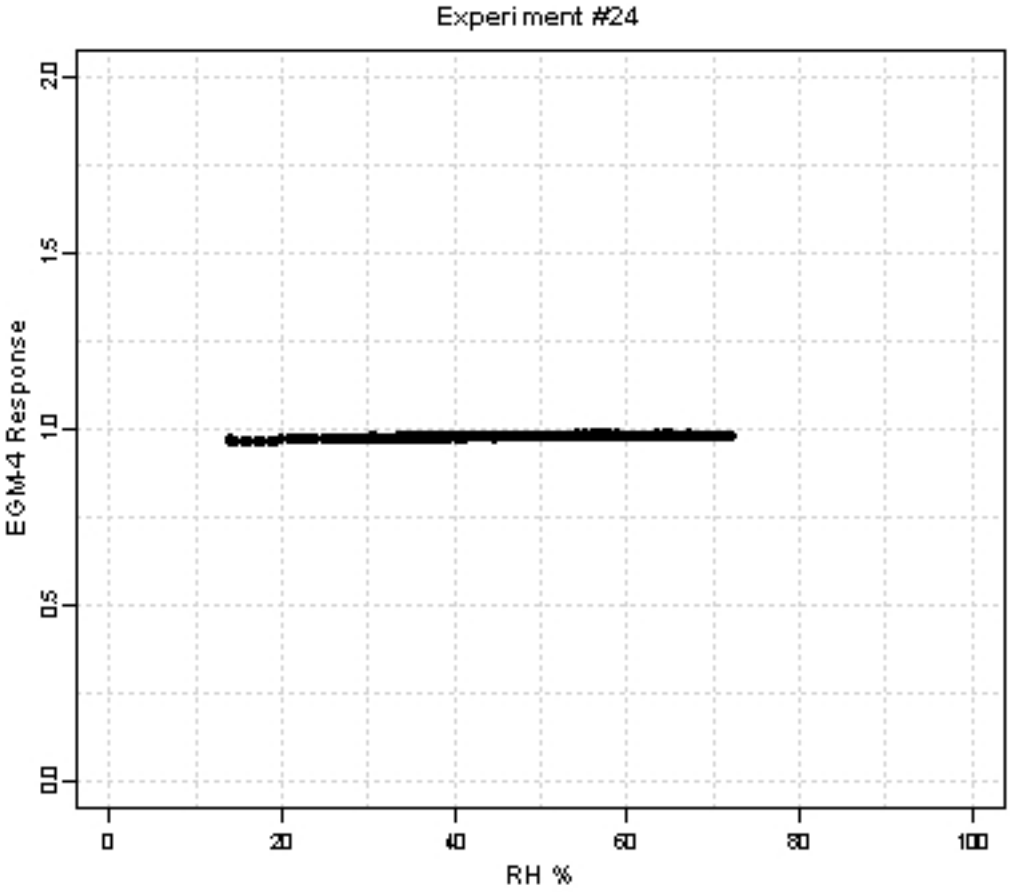
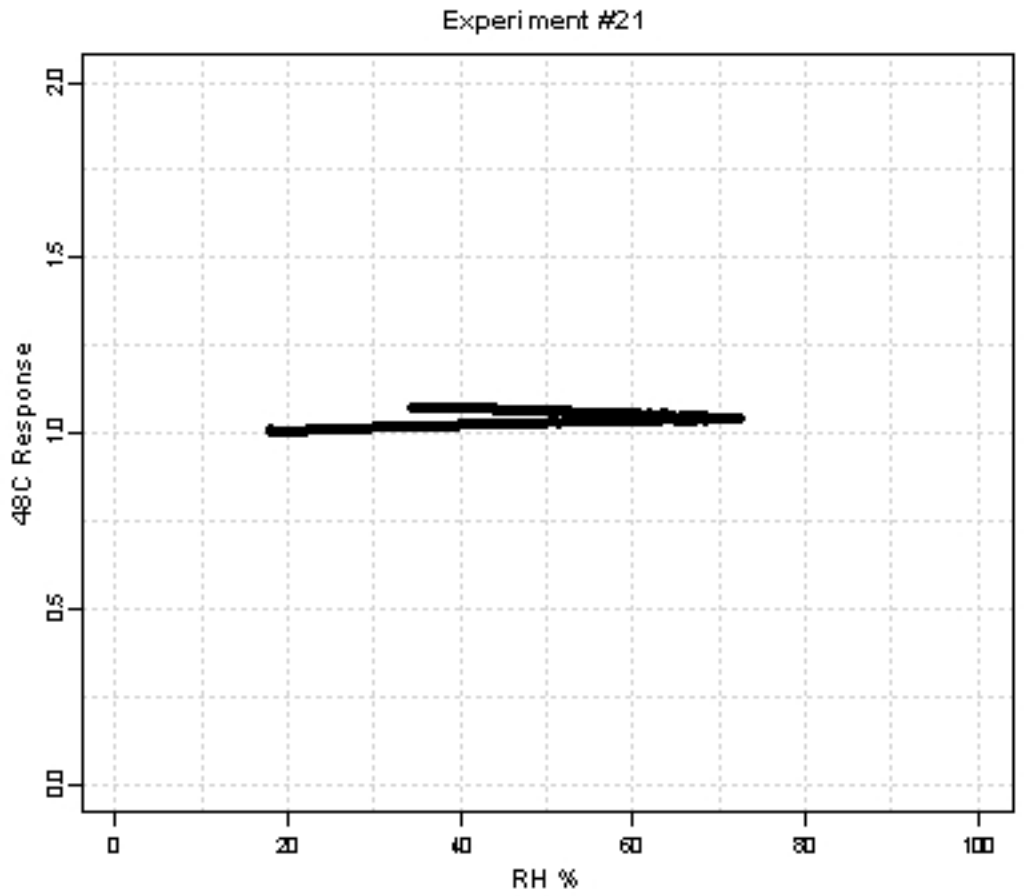
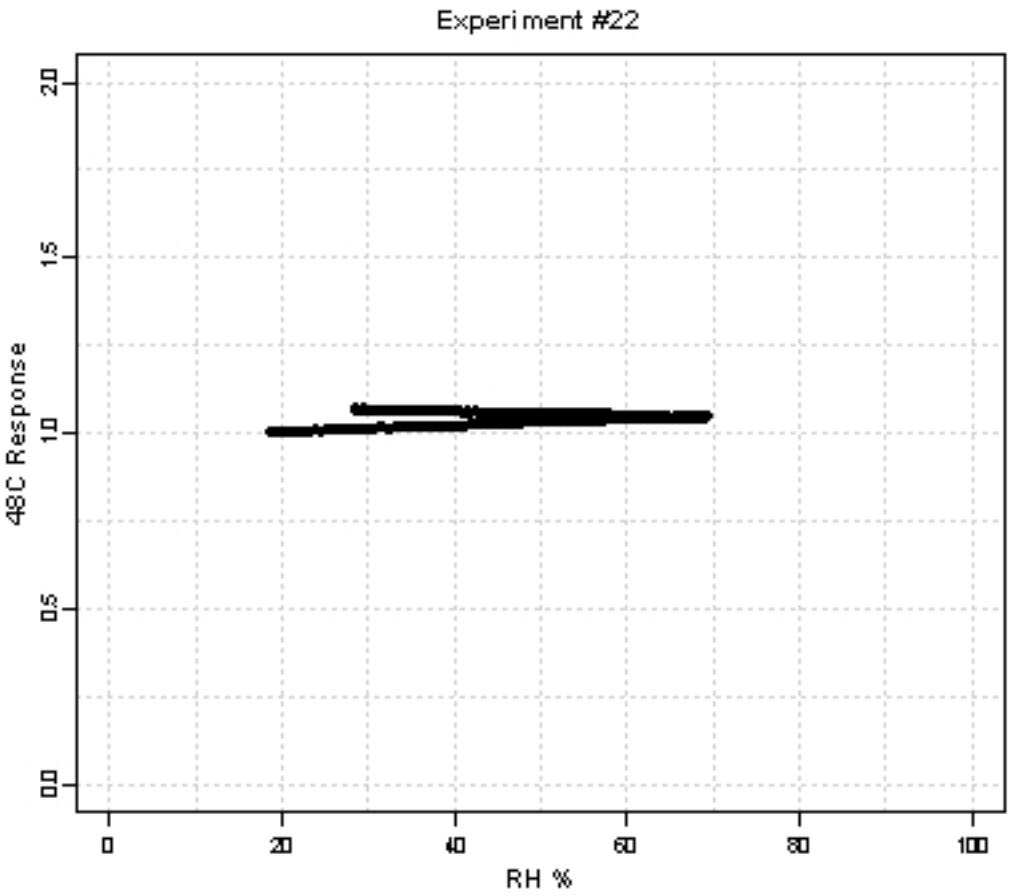
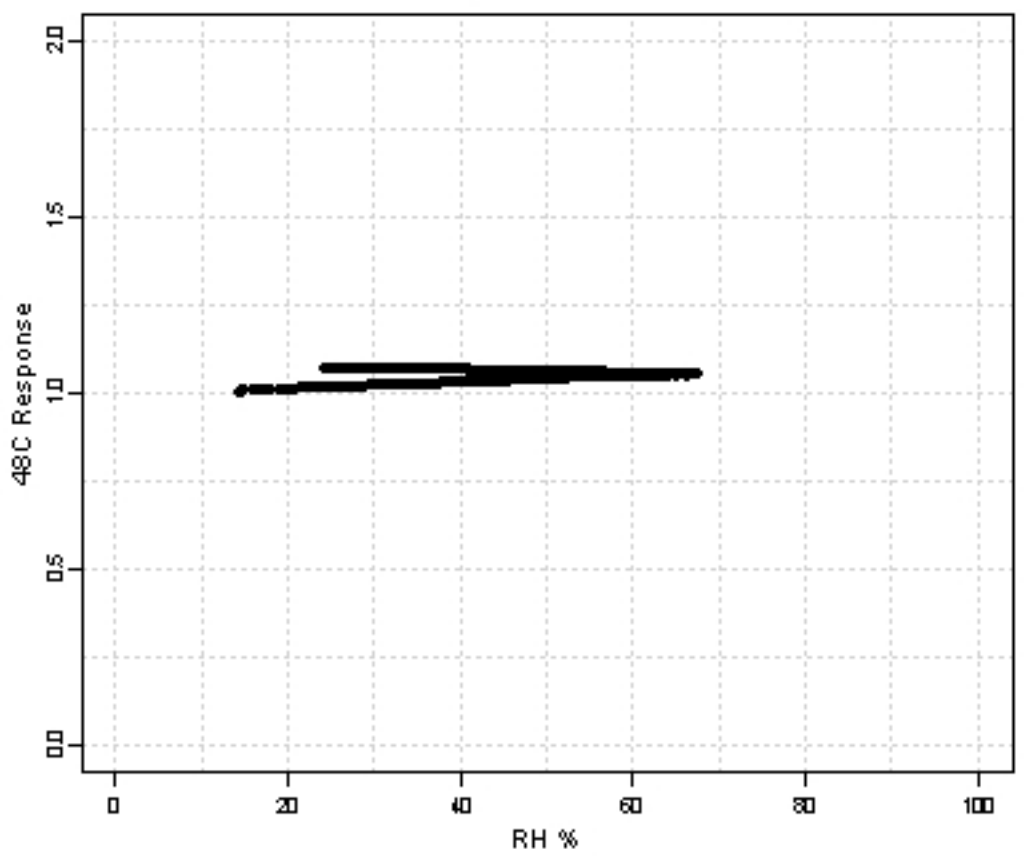


Fig. D28 CO/CO2 Tests: Variable Relative Humidity #2: 48C/48C CO (Expts 21-24)







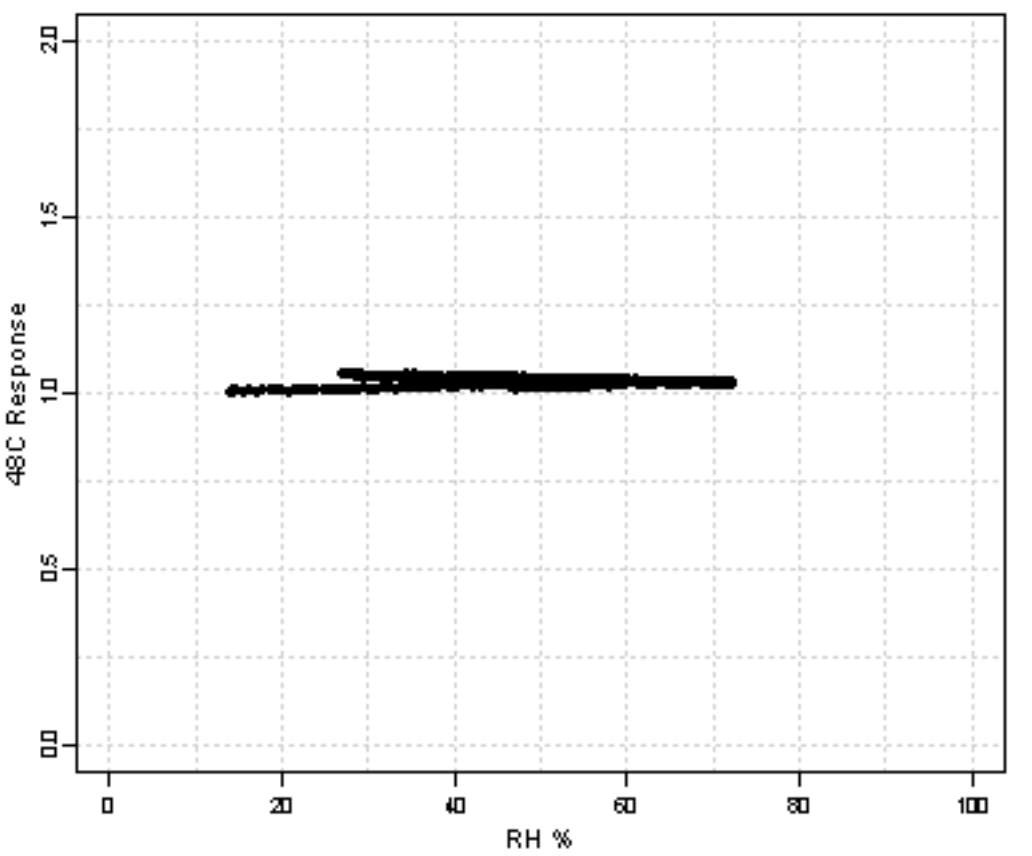
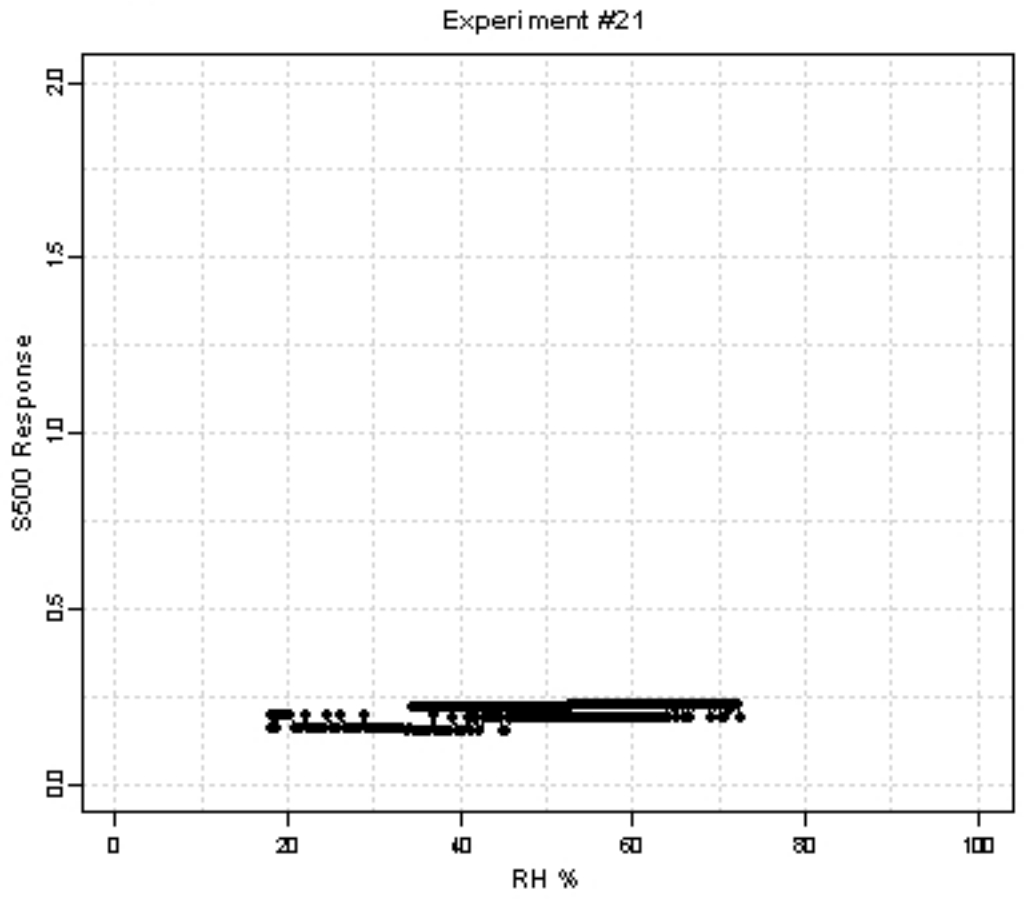
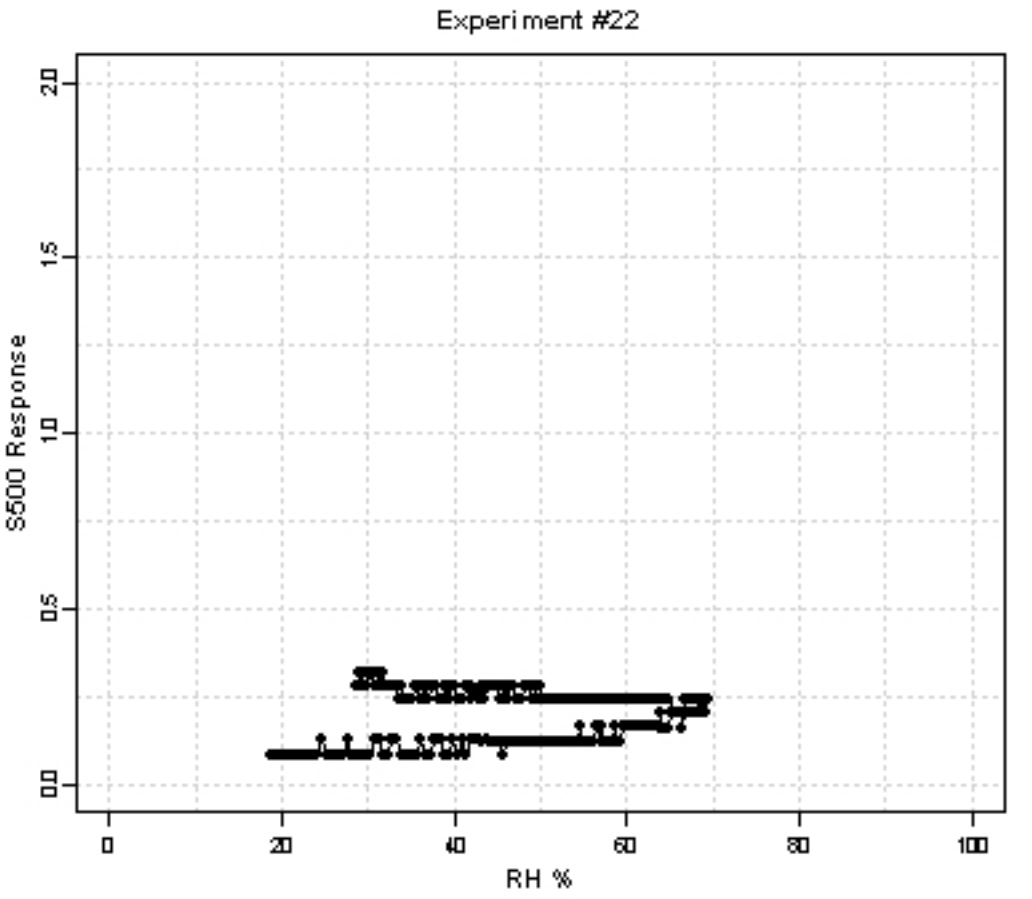
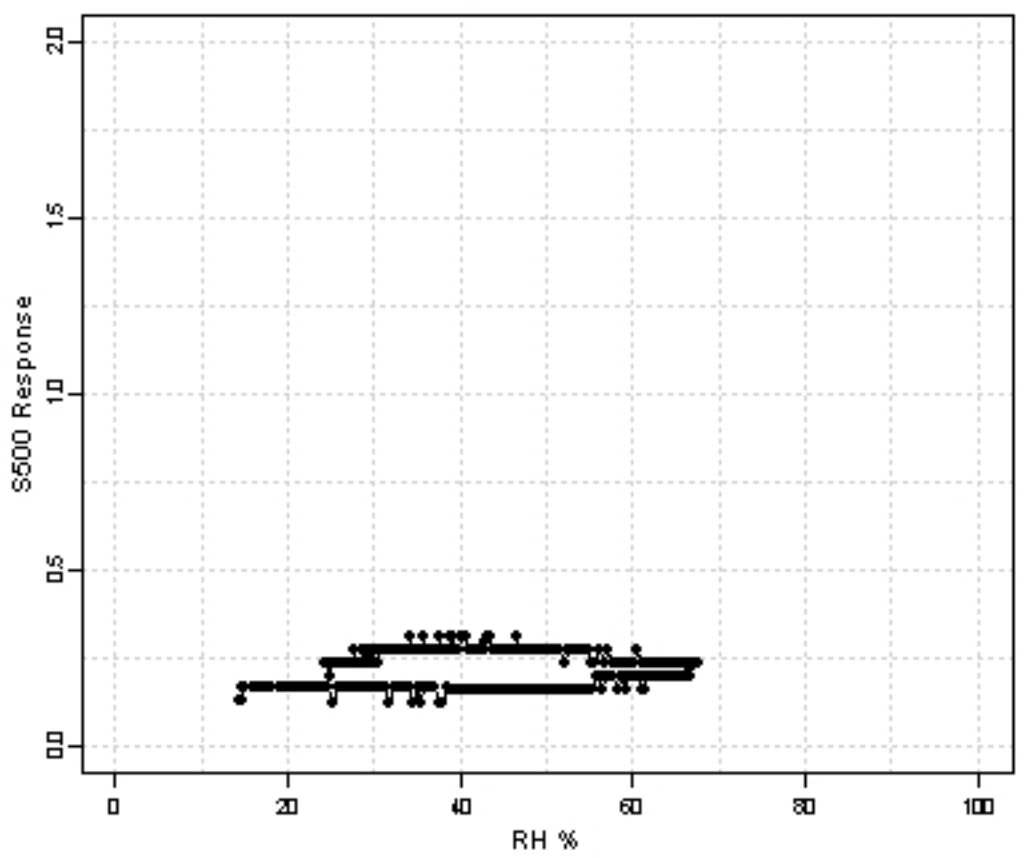


Fig. D29 CO/CO2 Tests: Variable Relative Humidity #2: S500/48C CO (Expts 21-24)







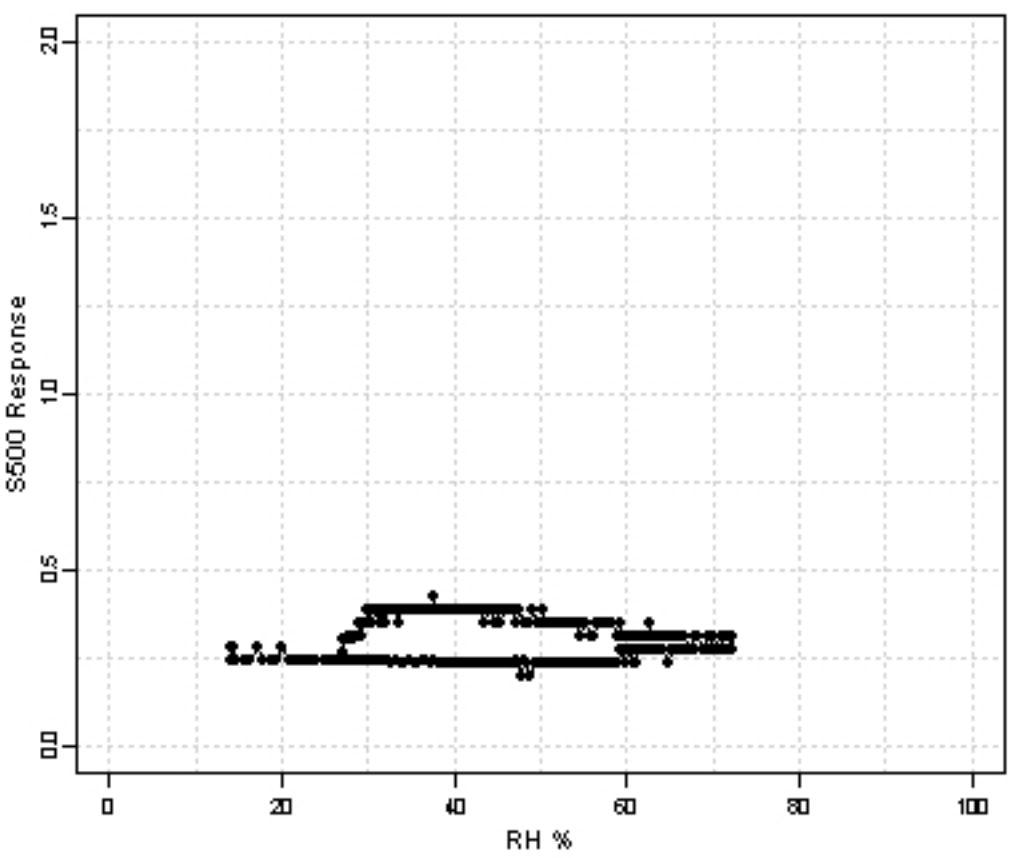
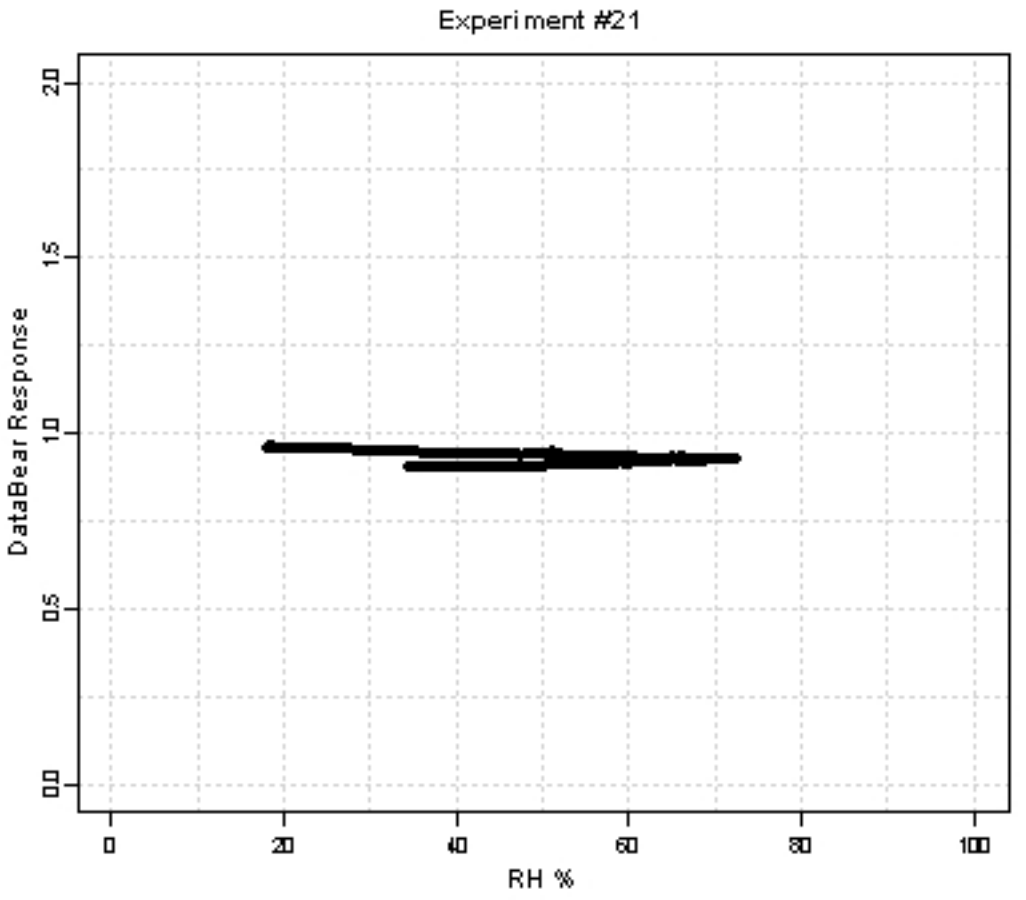
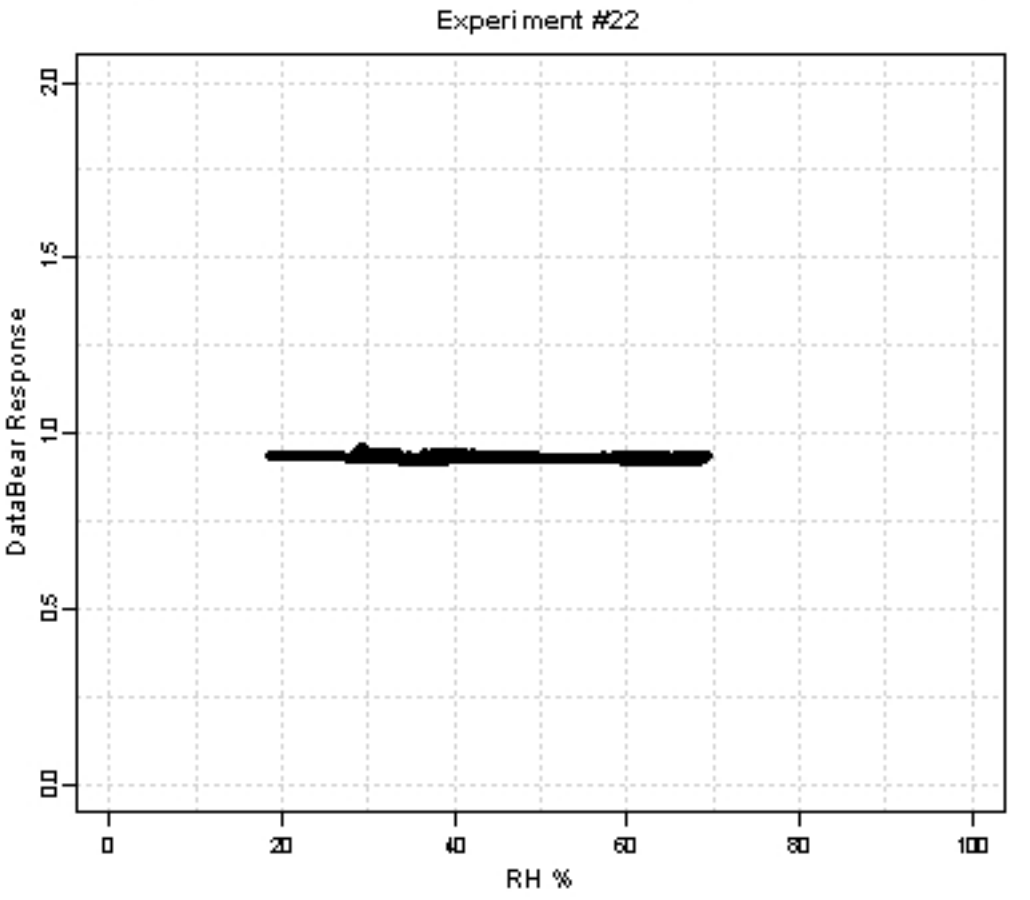
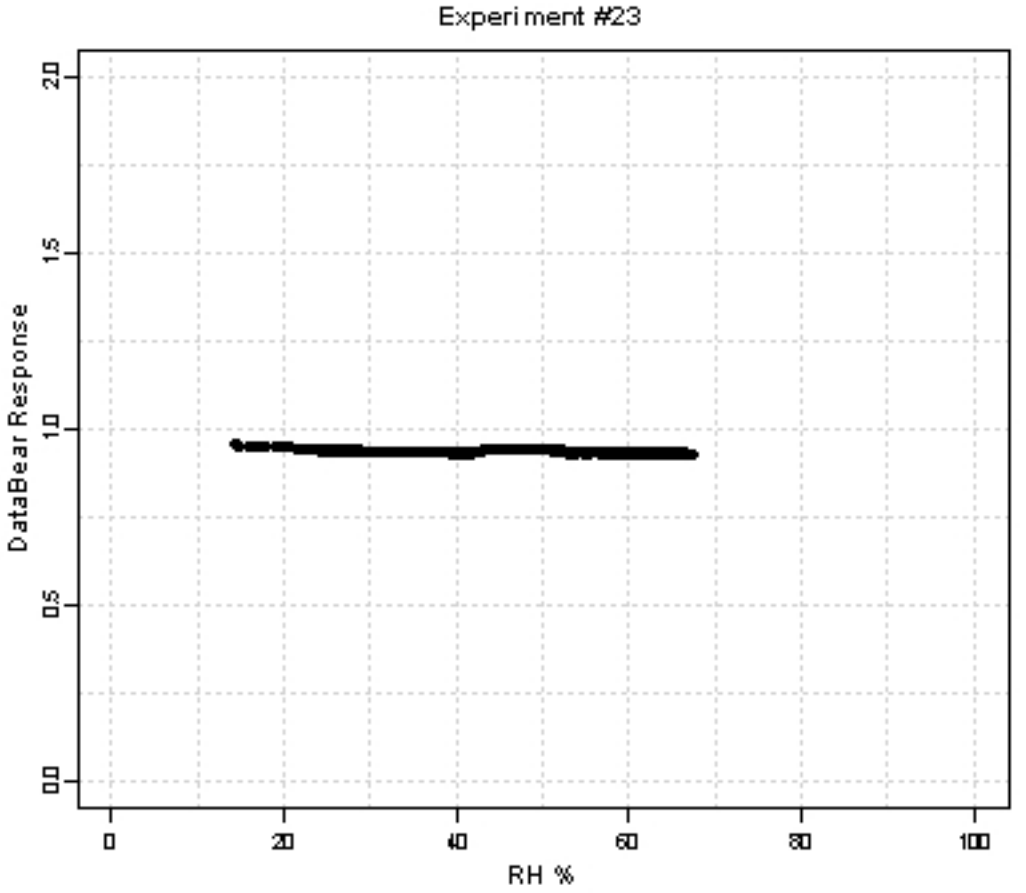


Fig. D30 CO/CO2 Tests: Variable Relative Humidity #2: DataBear/48C CO (Expts 21-24)







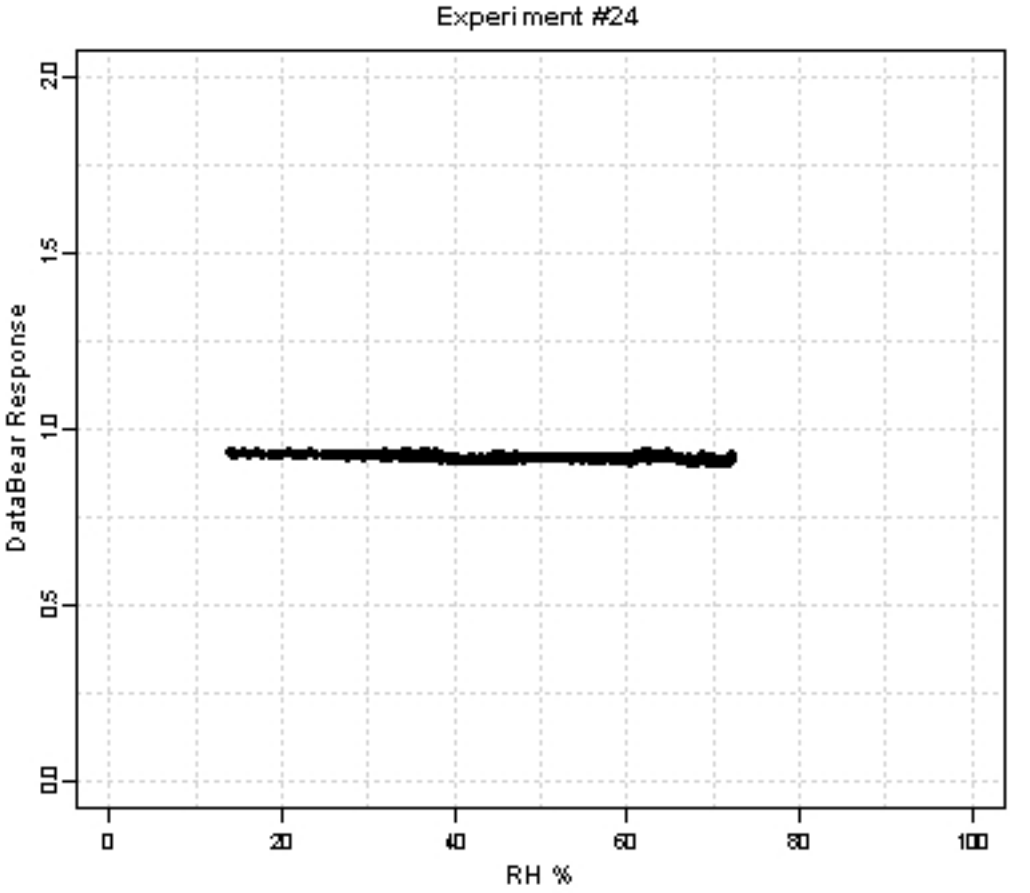
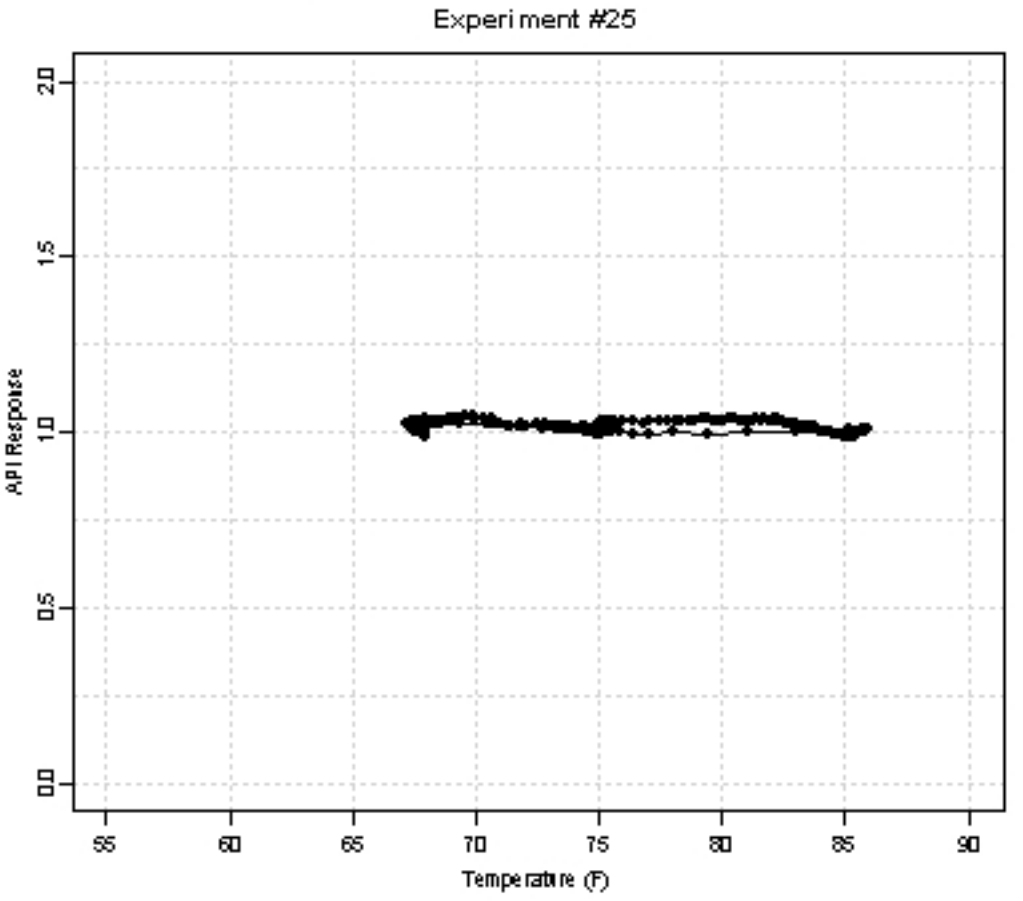


Fig. D31 Ozone Tests: Variable Temperature: API/API (Expts 25-26)



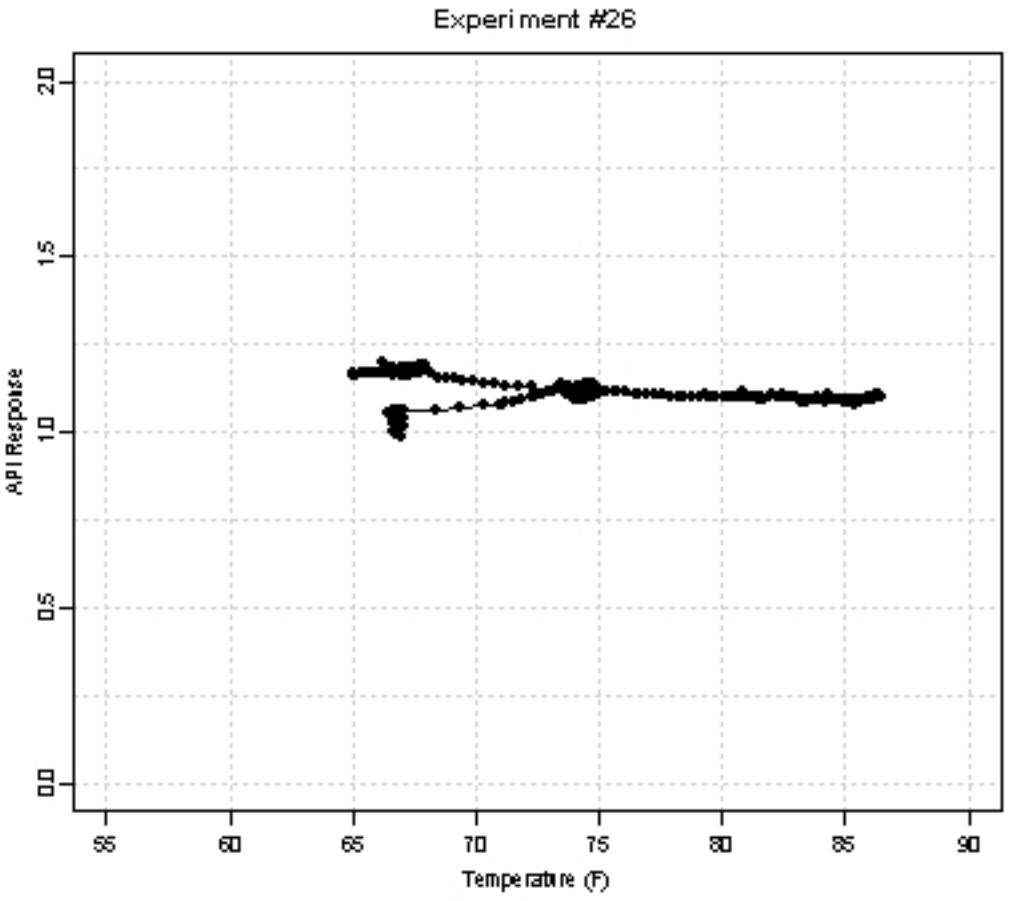
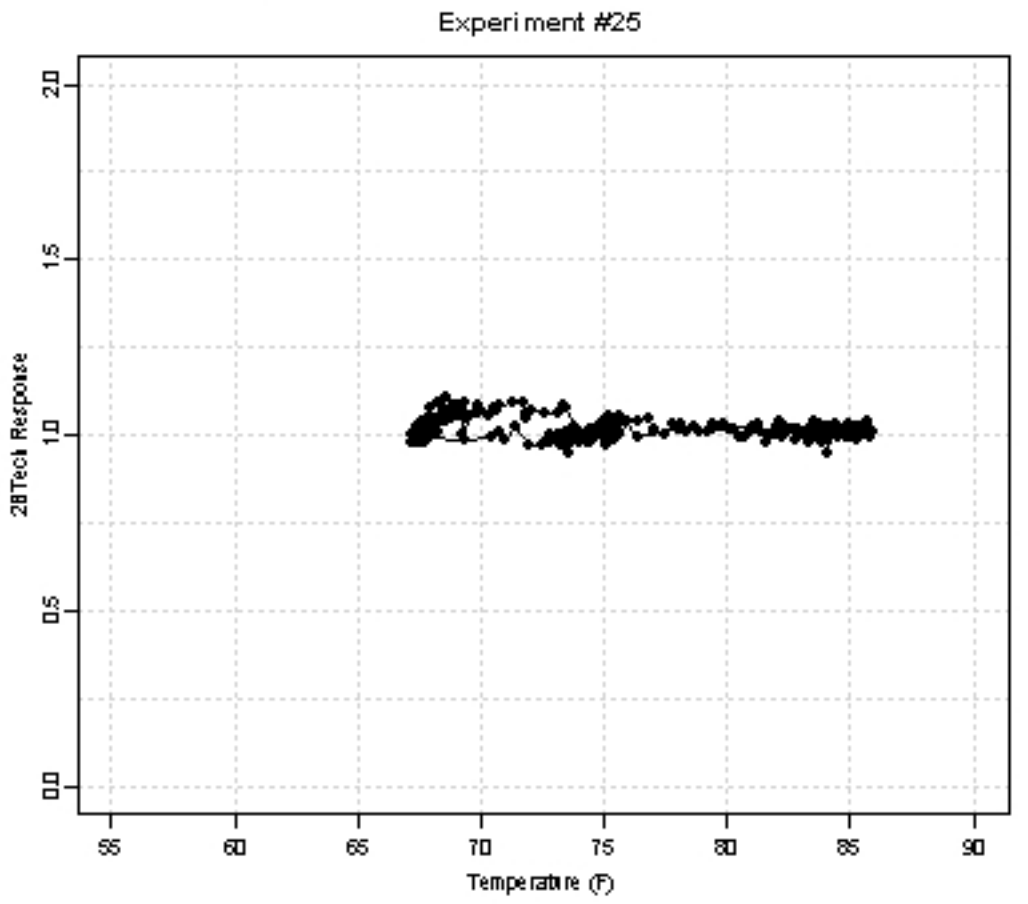


Fig. D32 Ozone Tests: Variable Temperature: 2BTech/API (Expts 25-26)



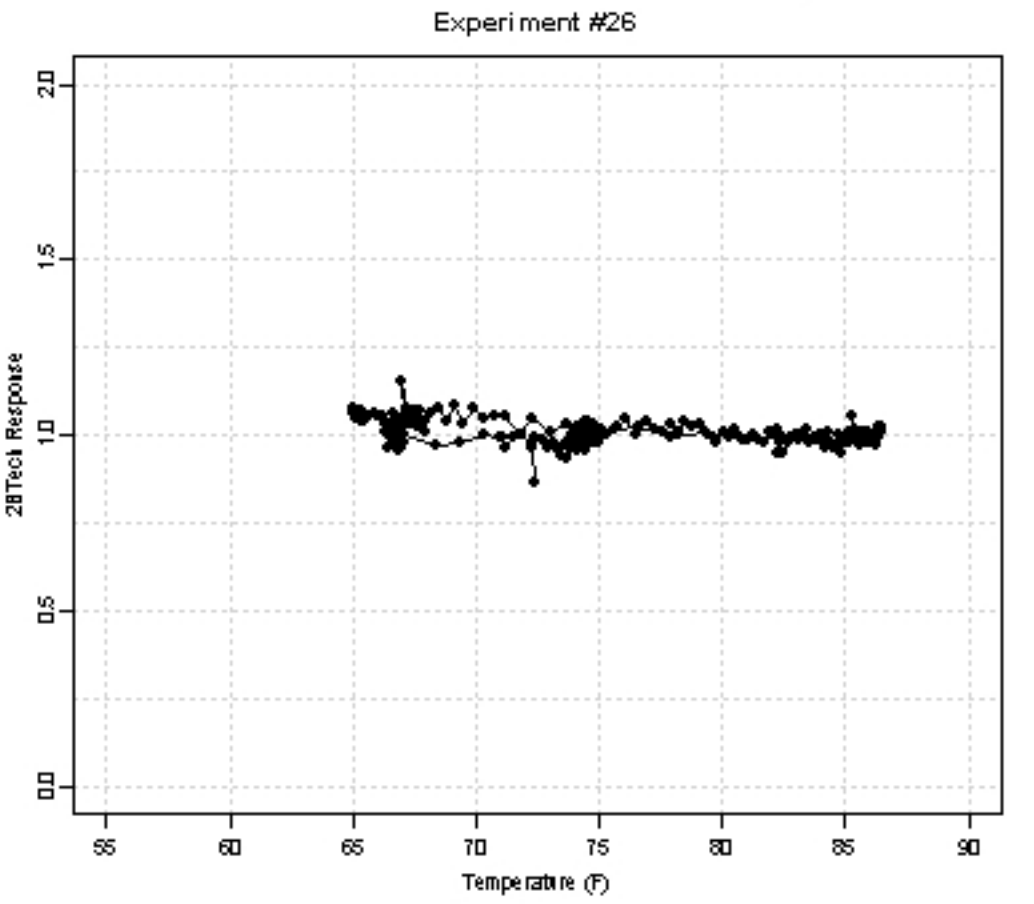
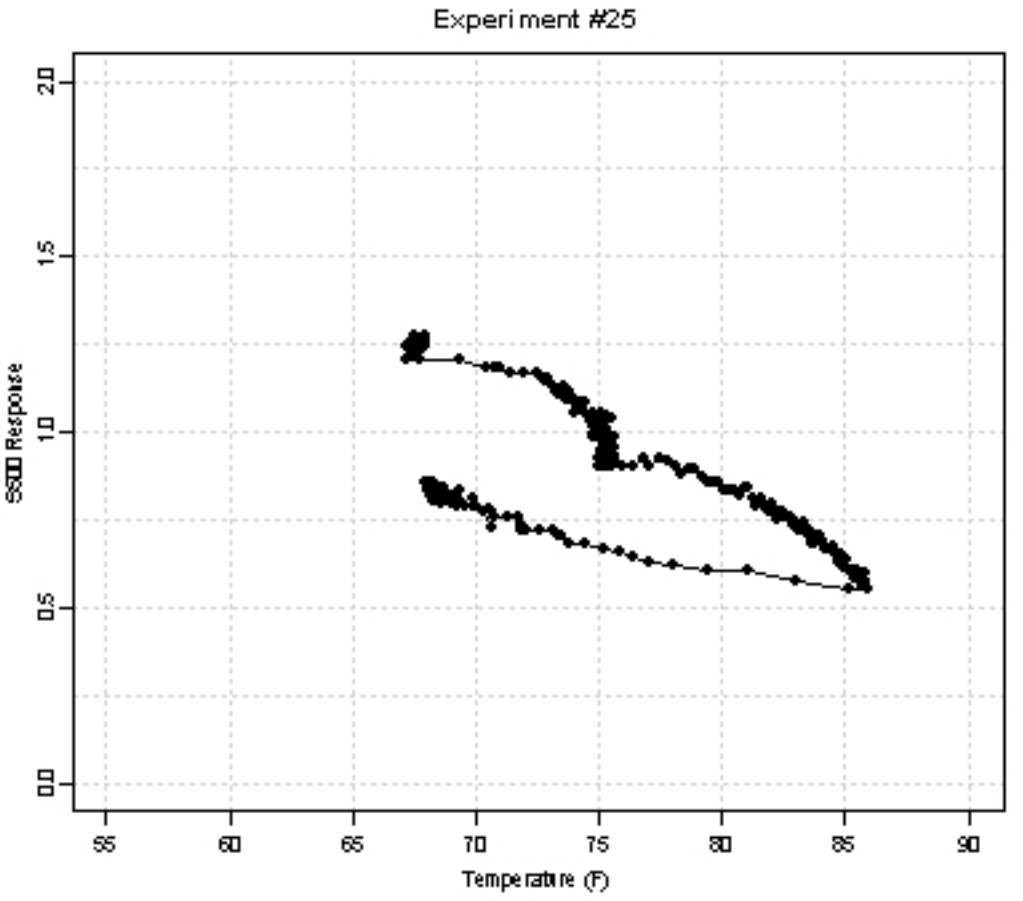


Fig. D33 Ozone Tests: Variable Temperature: S500/API (Expts 25-26)



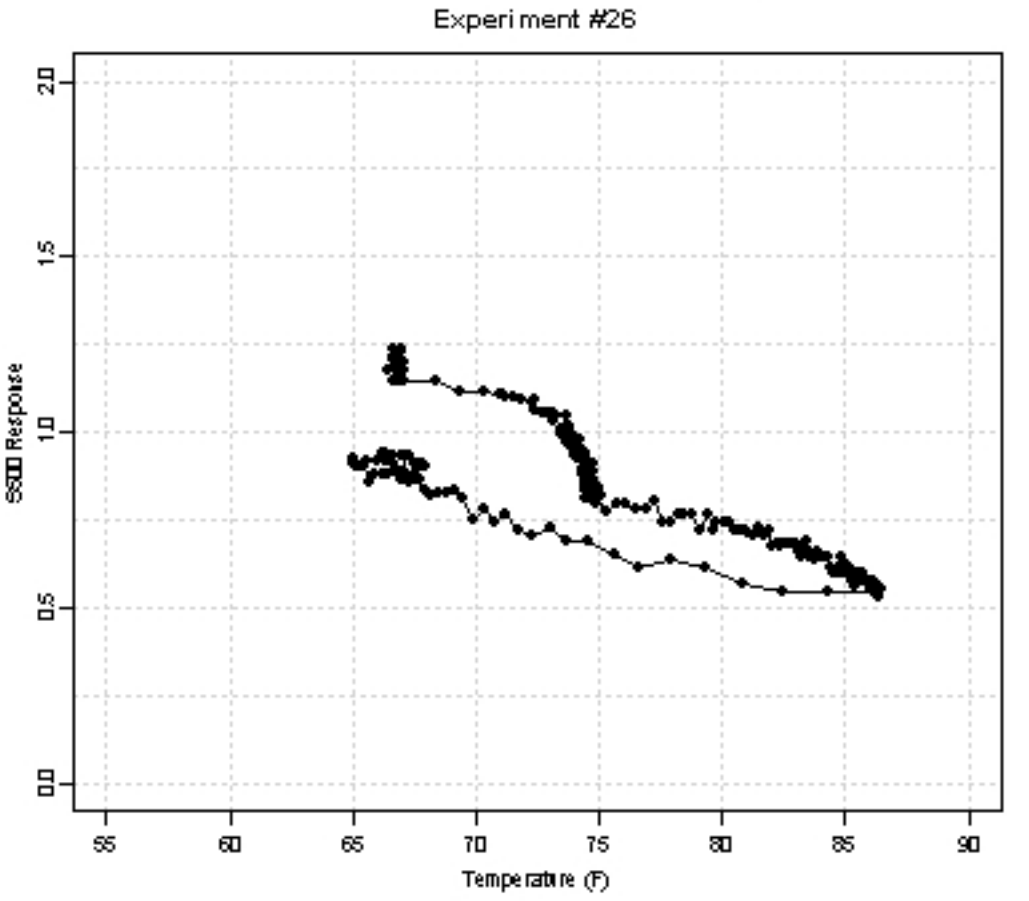


Fig. D34 Ozone Tests: Variable Temperature: OMC-1108/API (Expts 25-26)

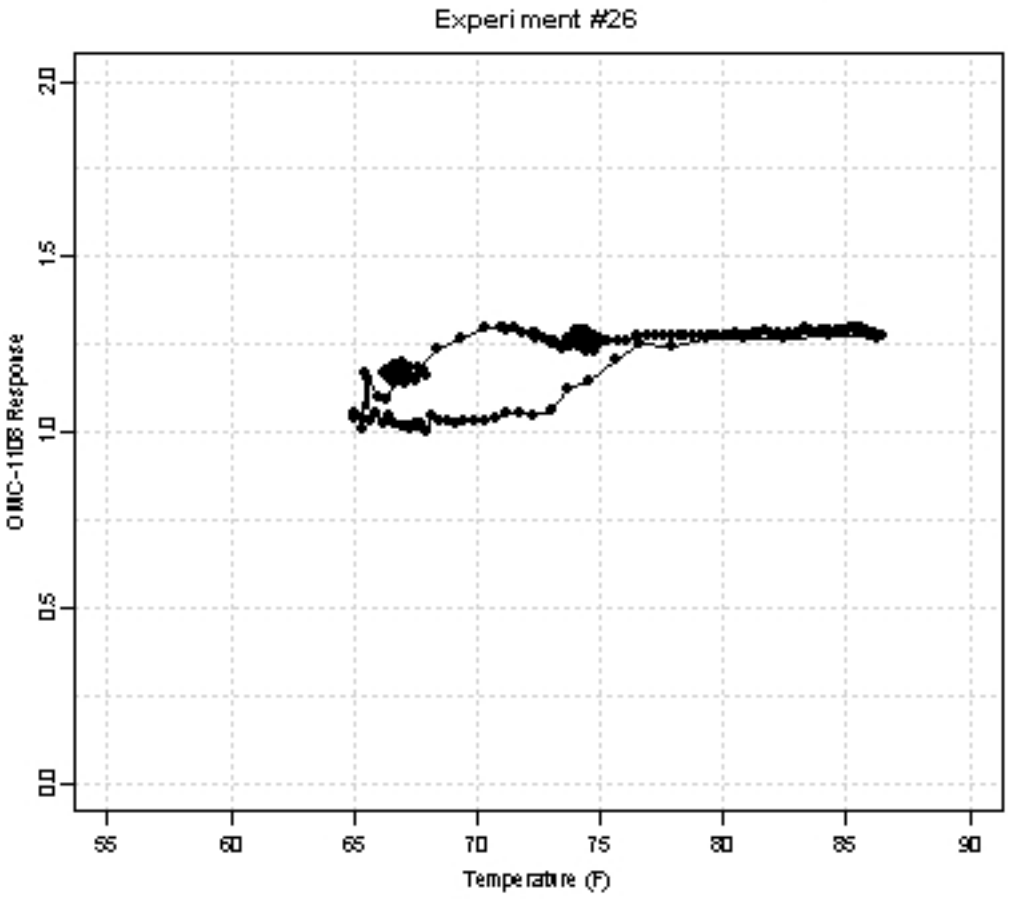
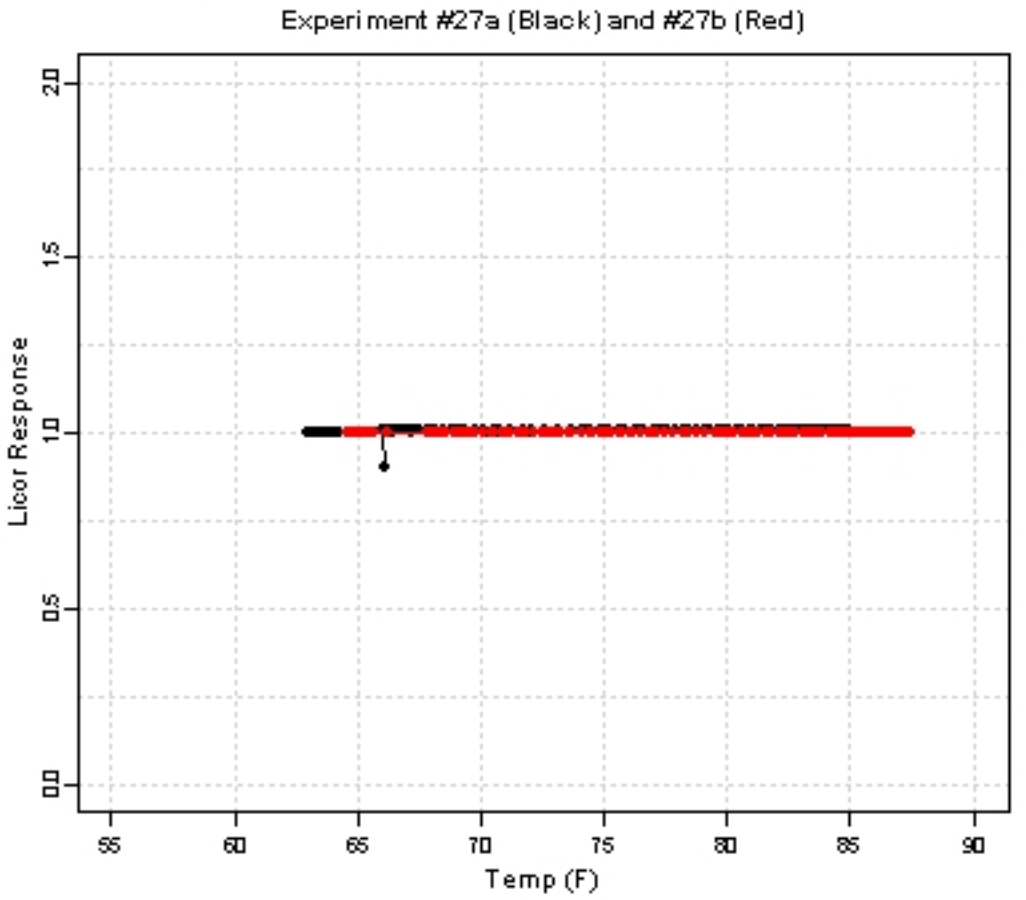
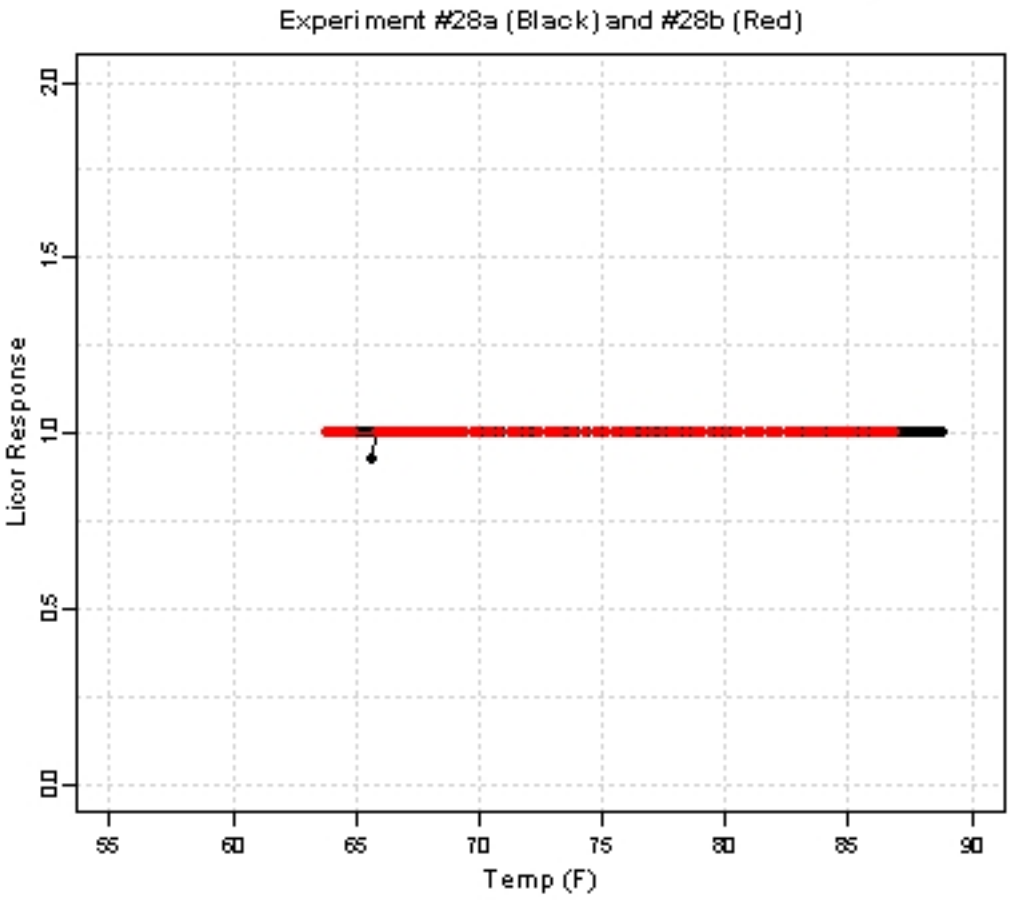
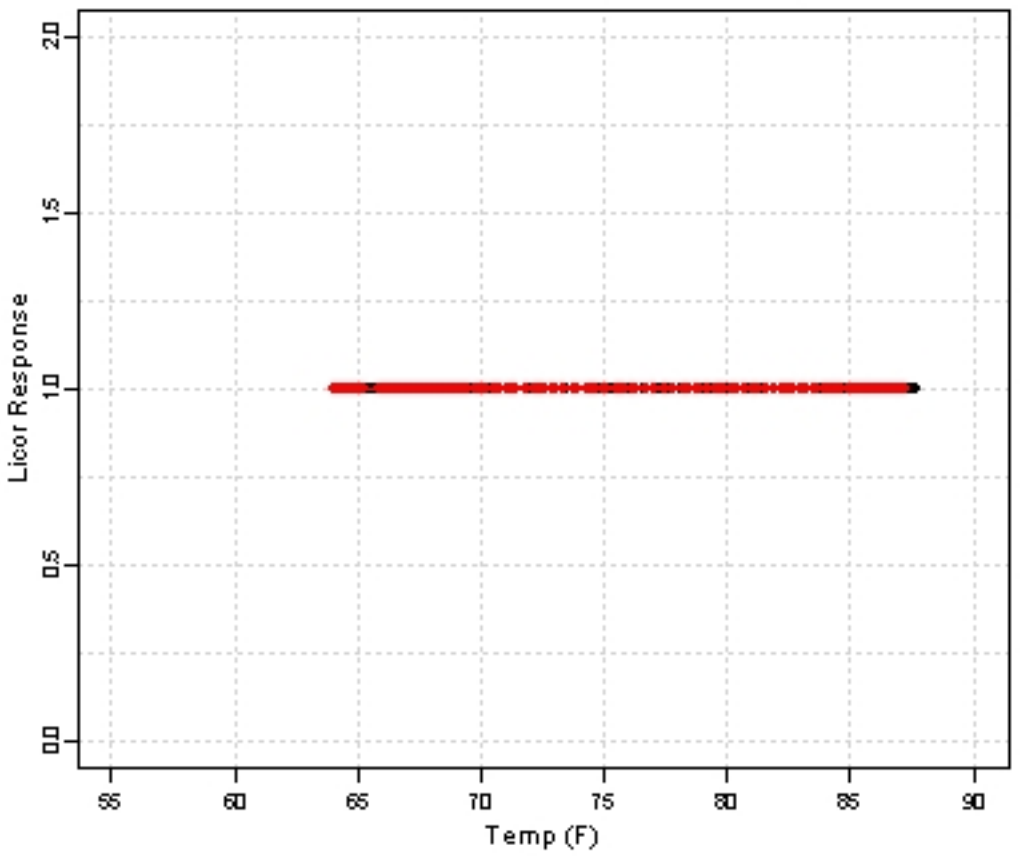
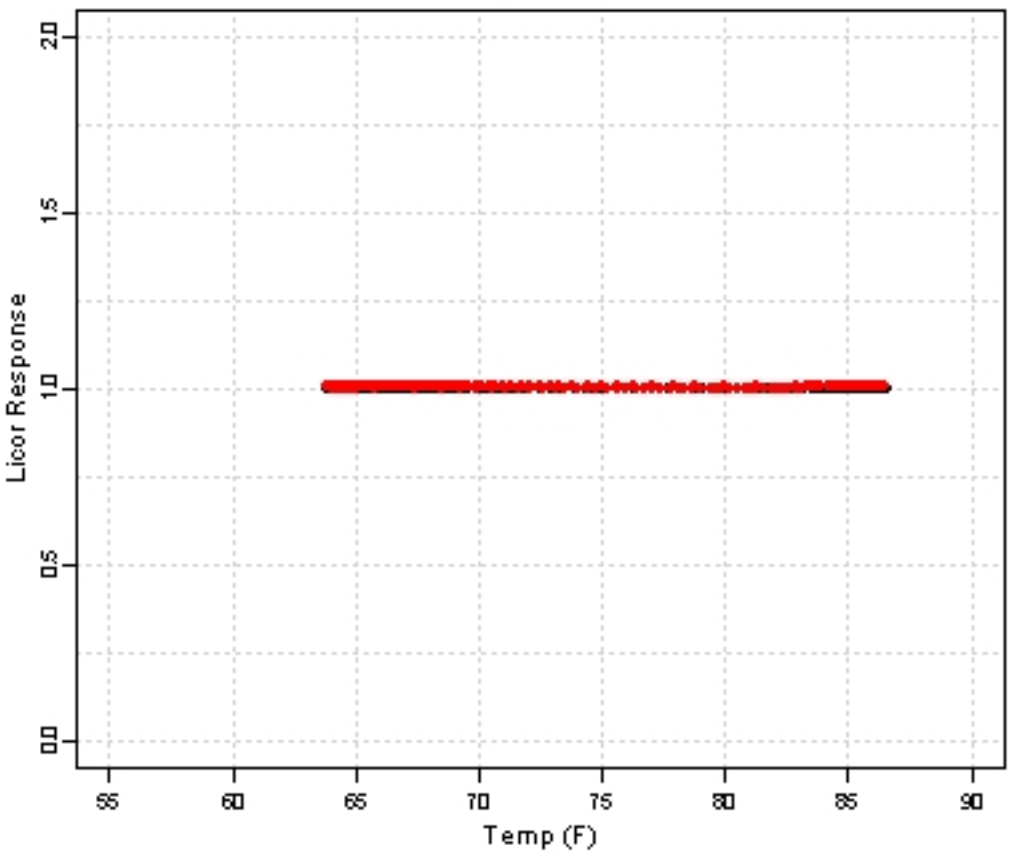


Fig. D35 CO/CO2 Tests: Variable Temperature: Licor/Licor CO2 (Expts 27-31)









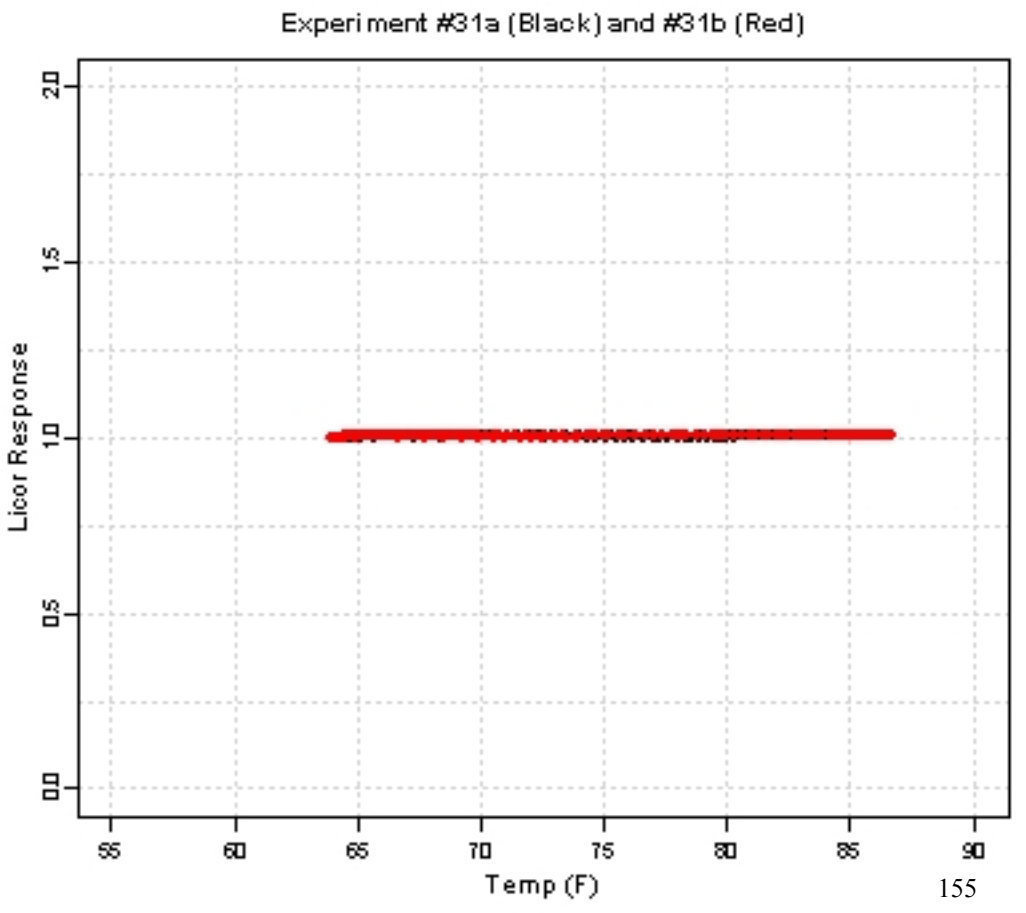
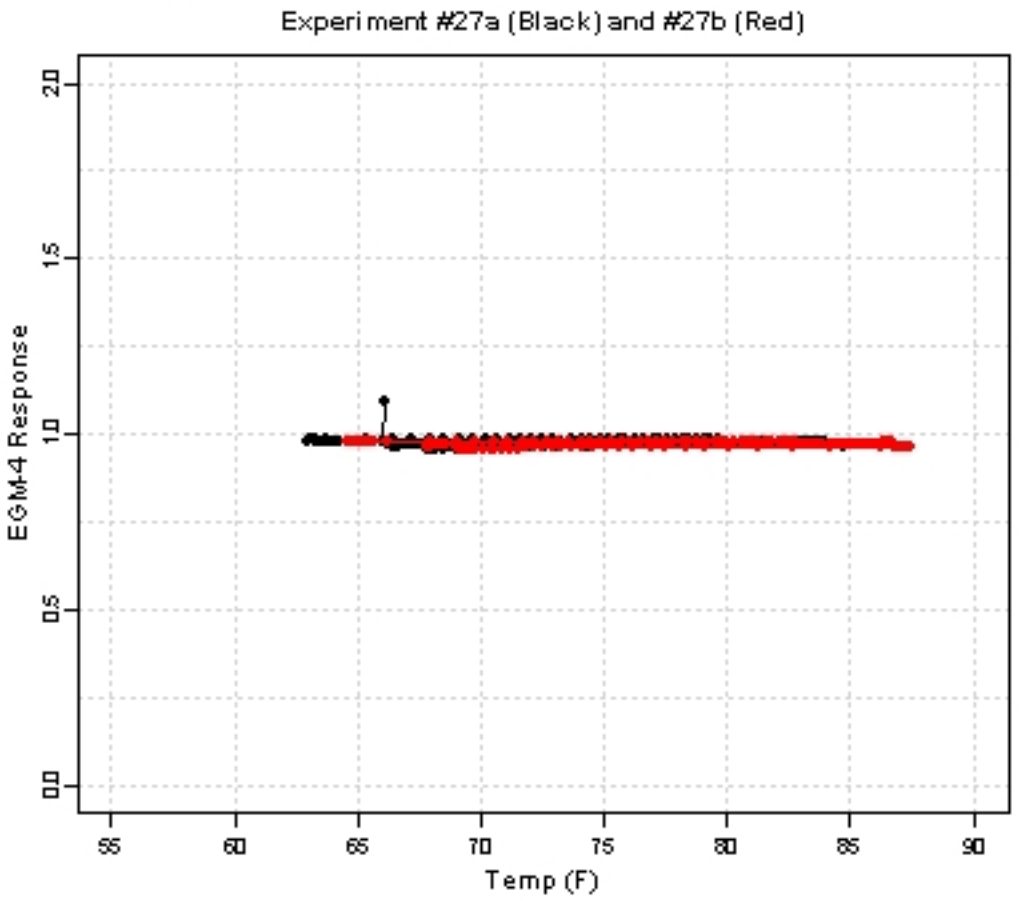
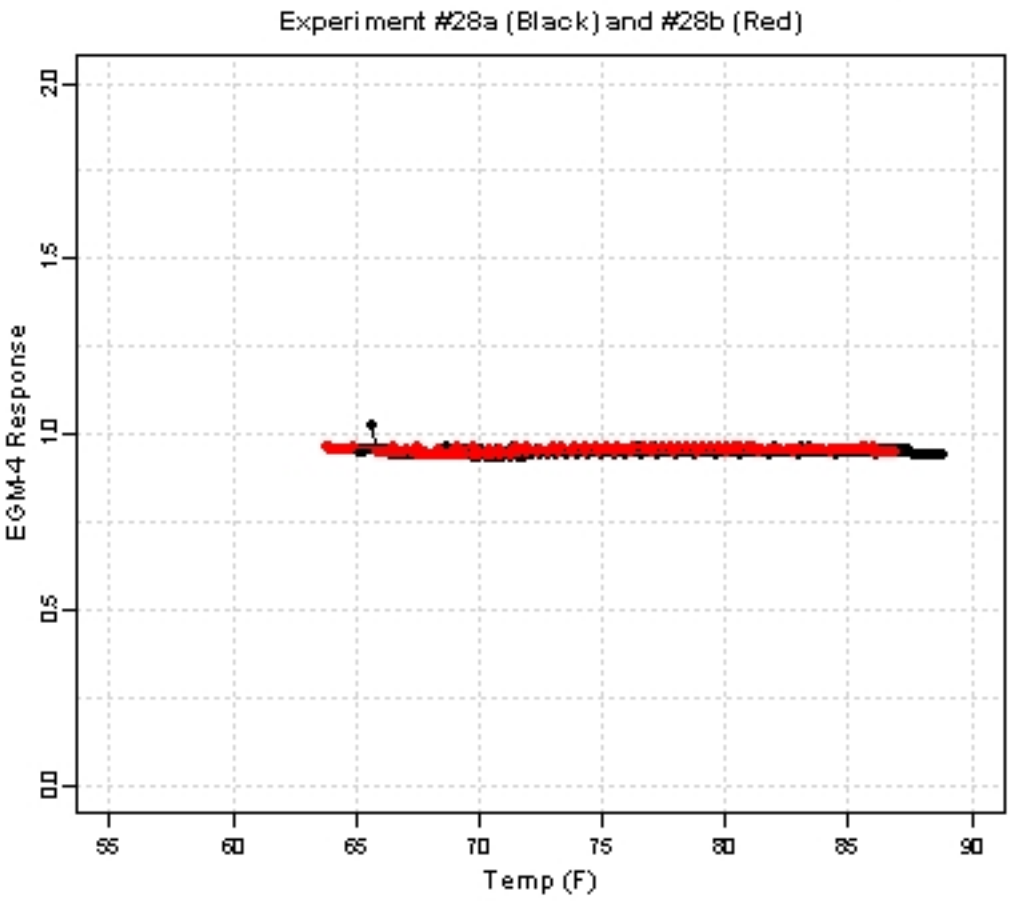
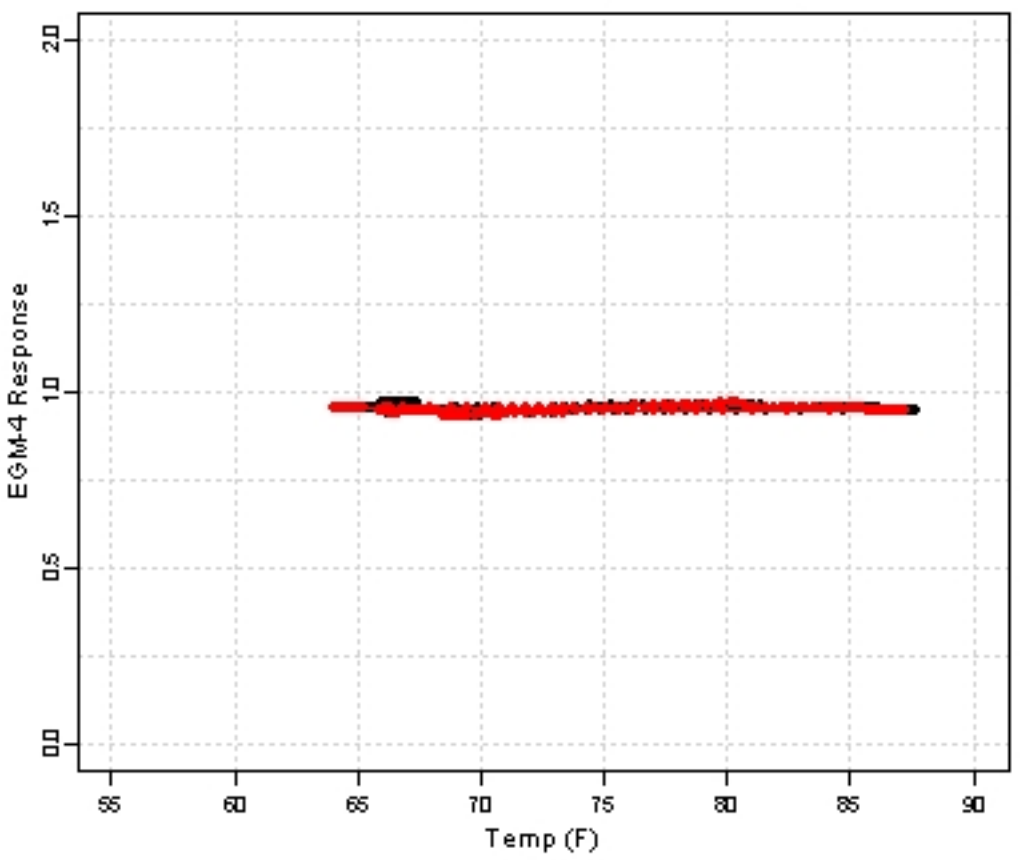
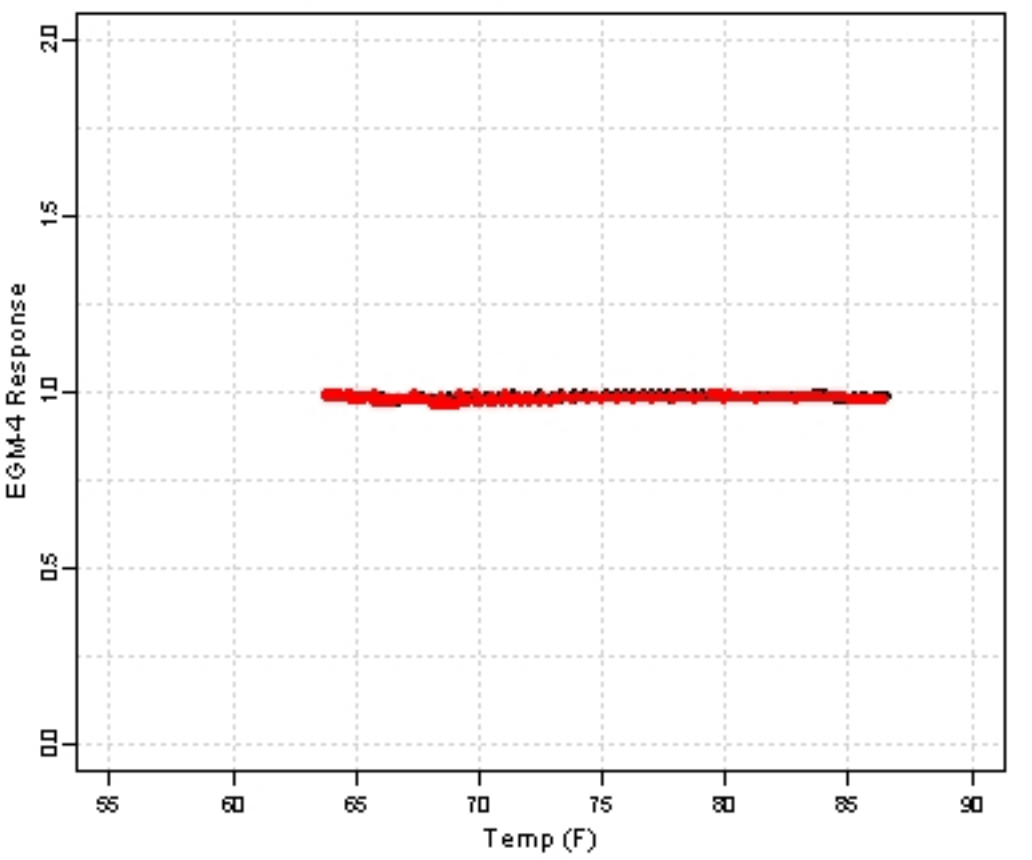


Fig. D36 CO/CO2 Tests: Variable Temperature: EGM-4/Licor CO2 (Expts 27-31)









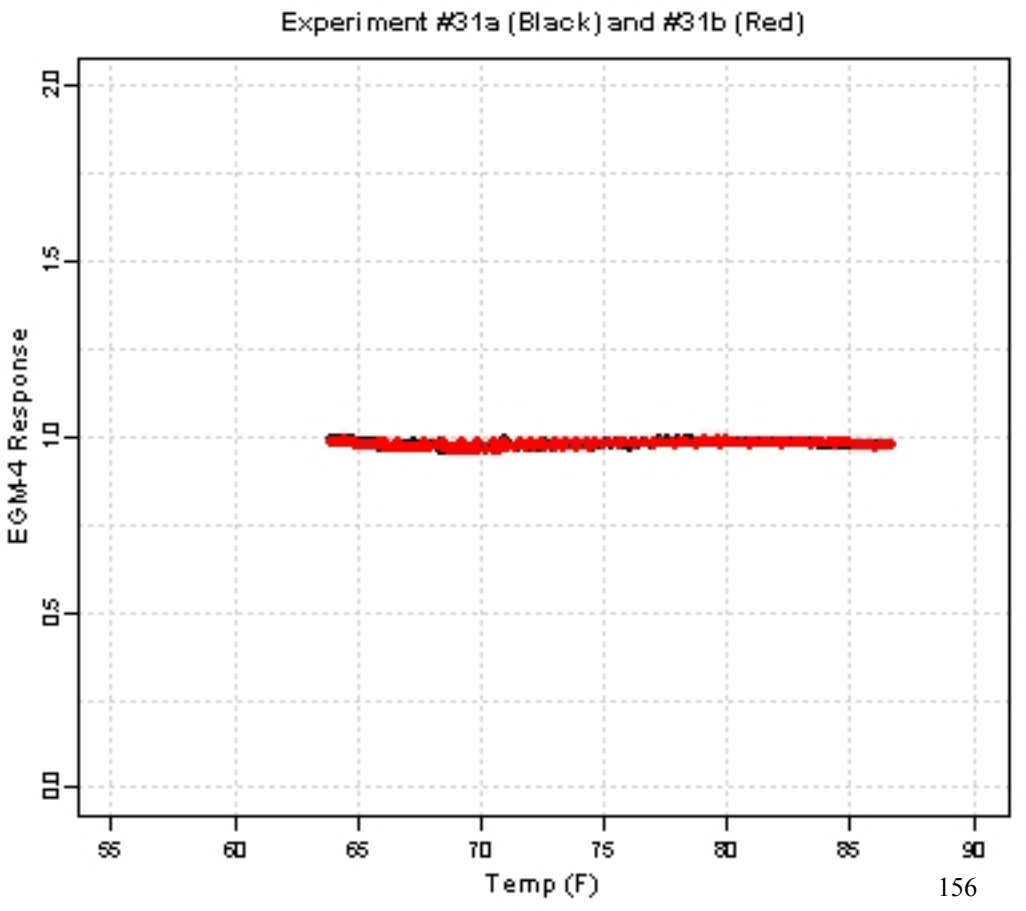
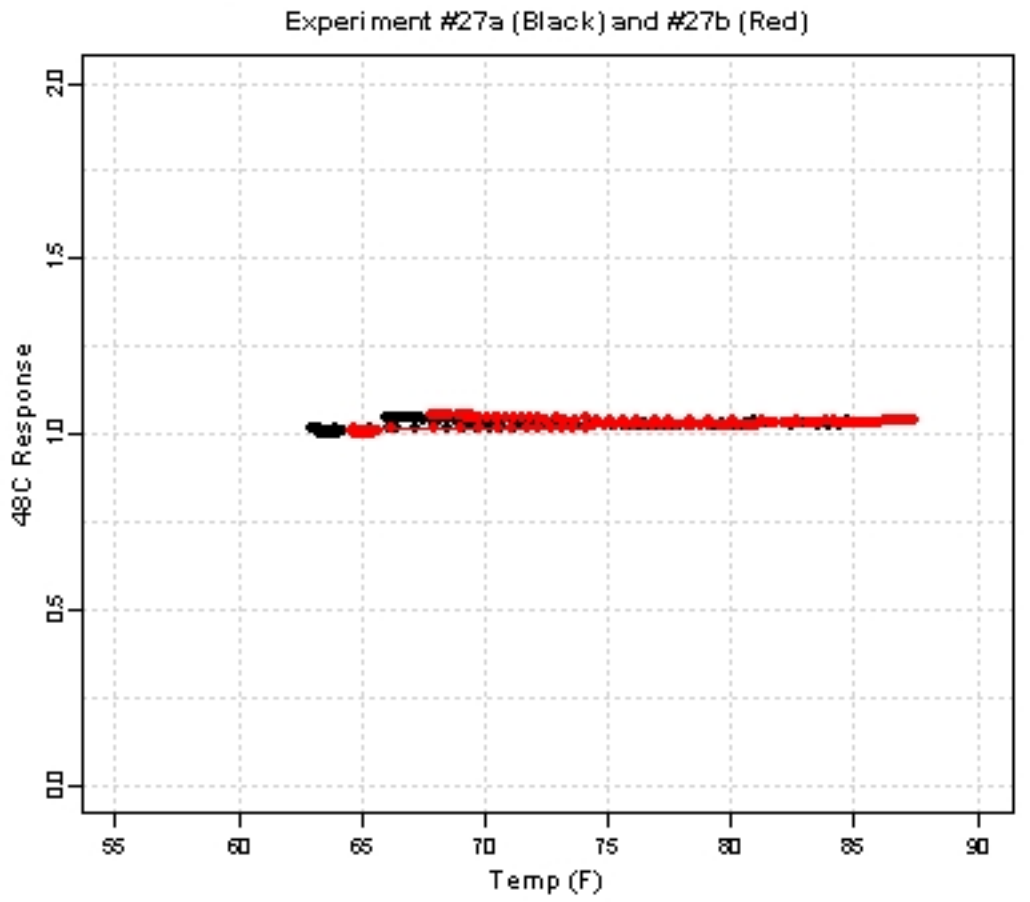
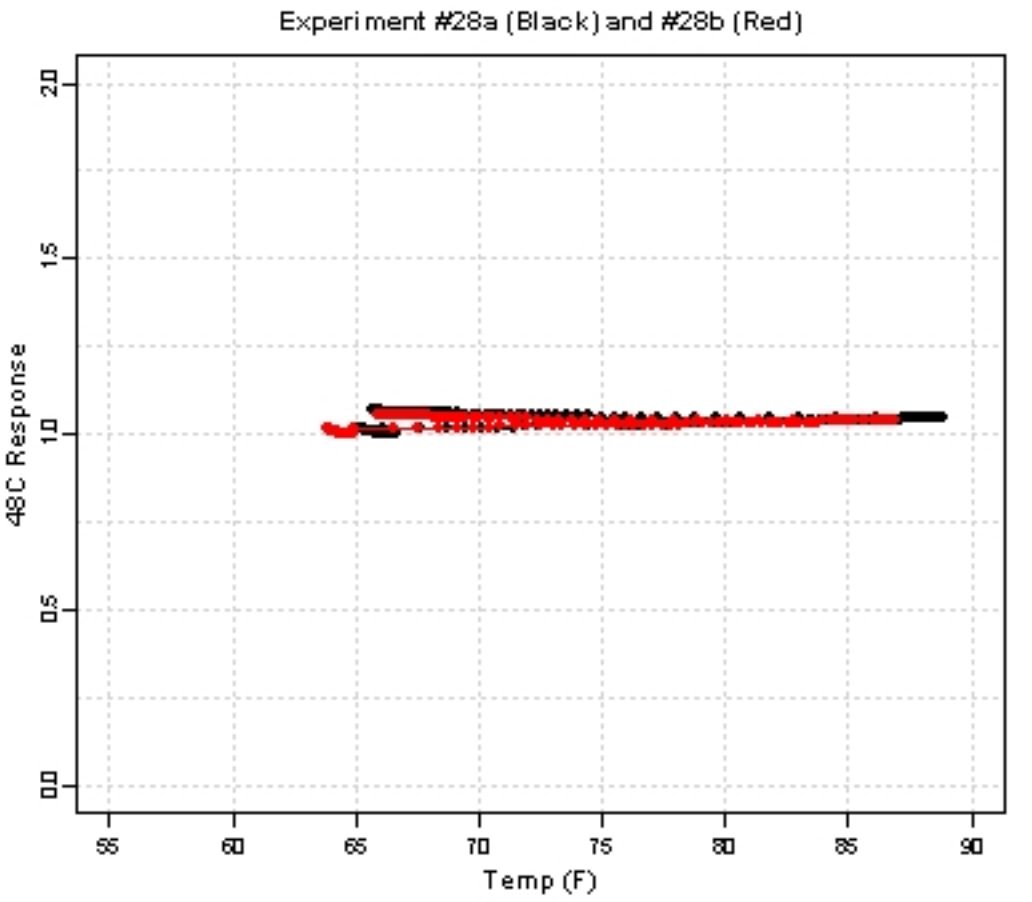
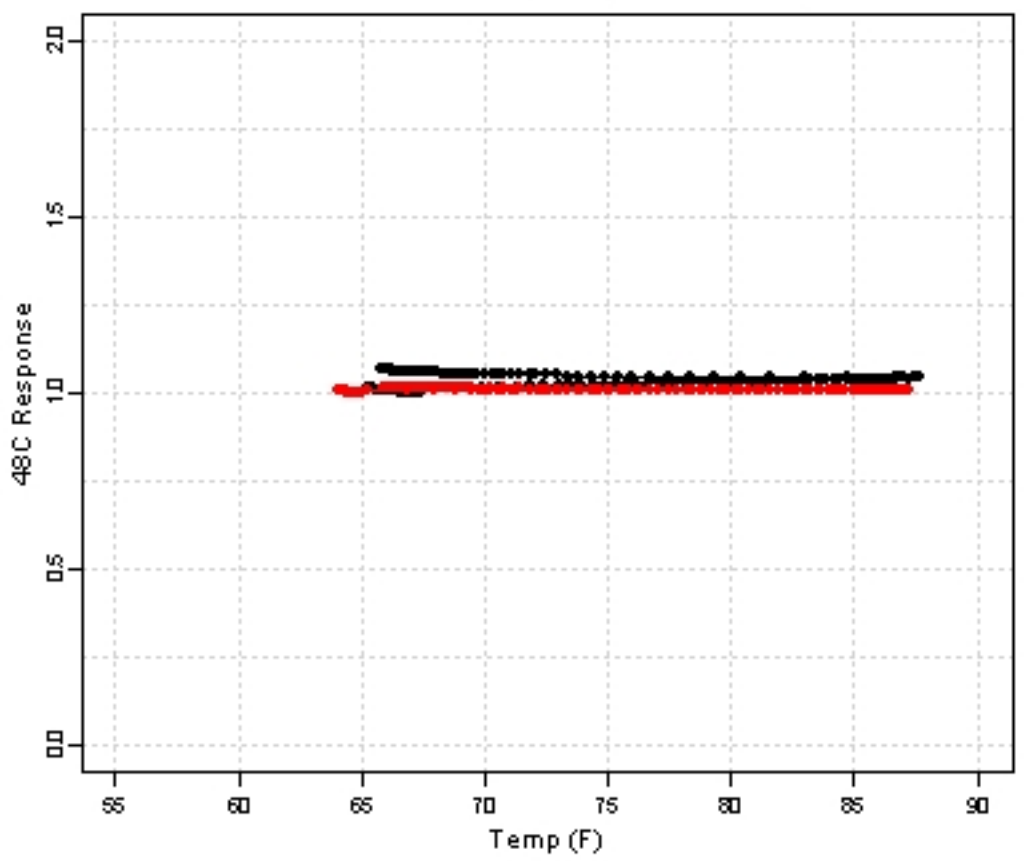
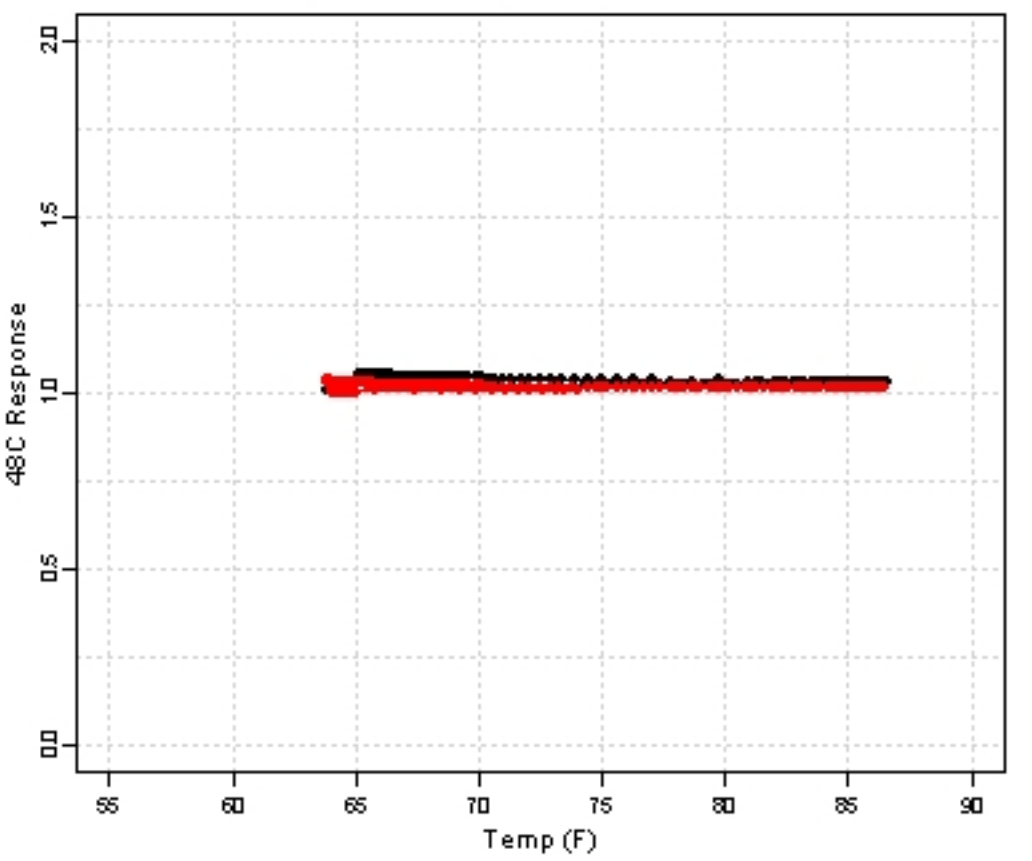


Fig. D37 CO/CO2 Tests: Variable Temperature: 48C/48C CO (Expts 27-31)









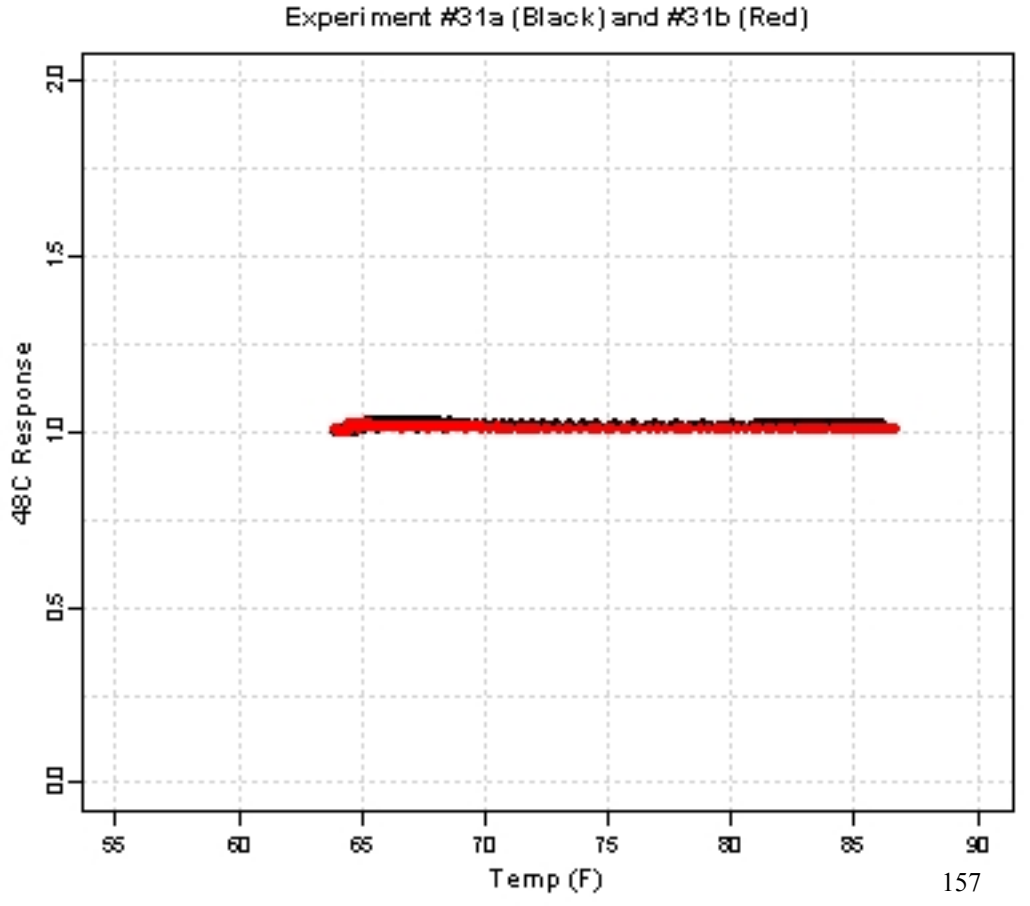
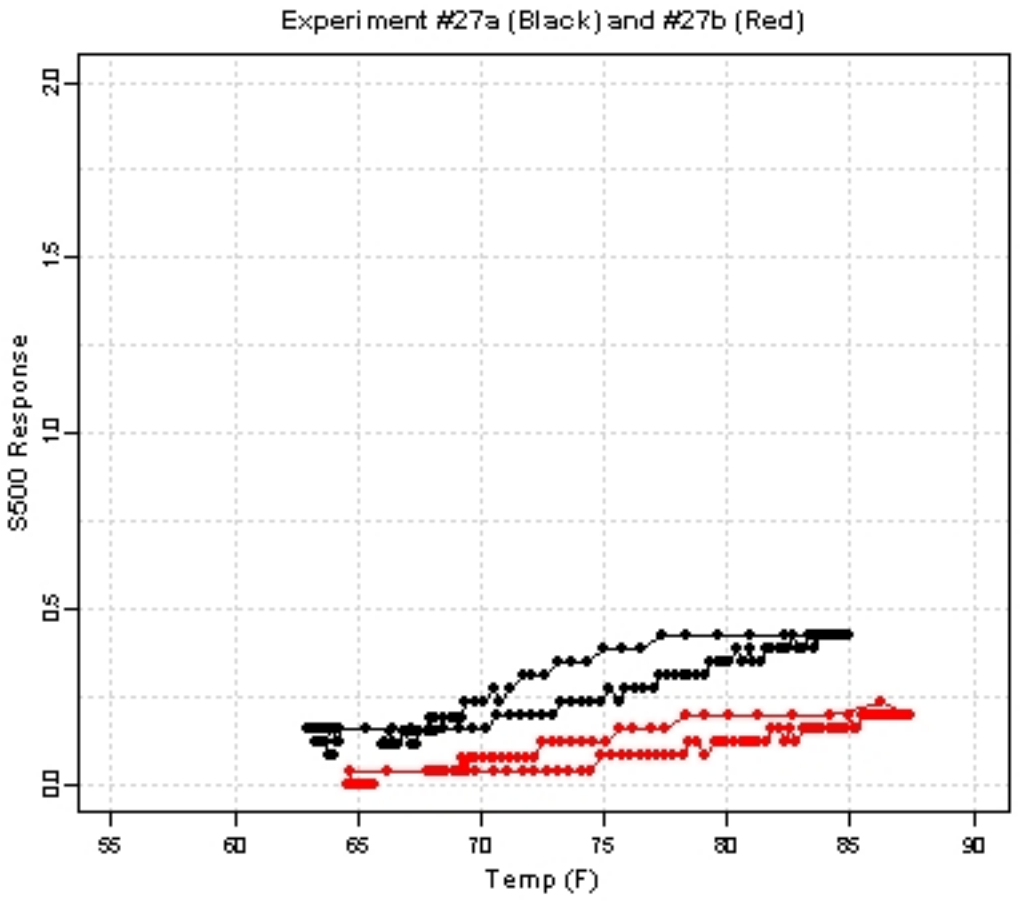
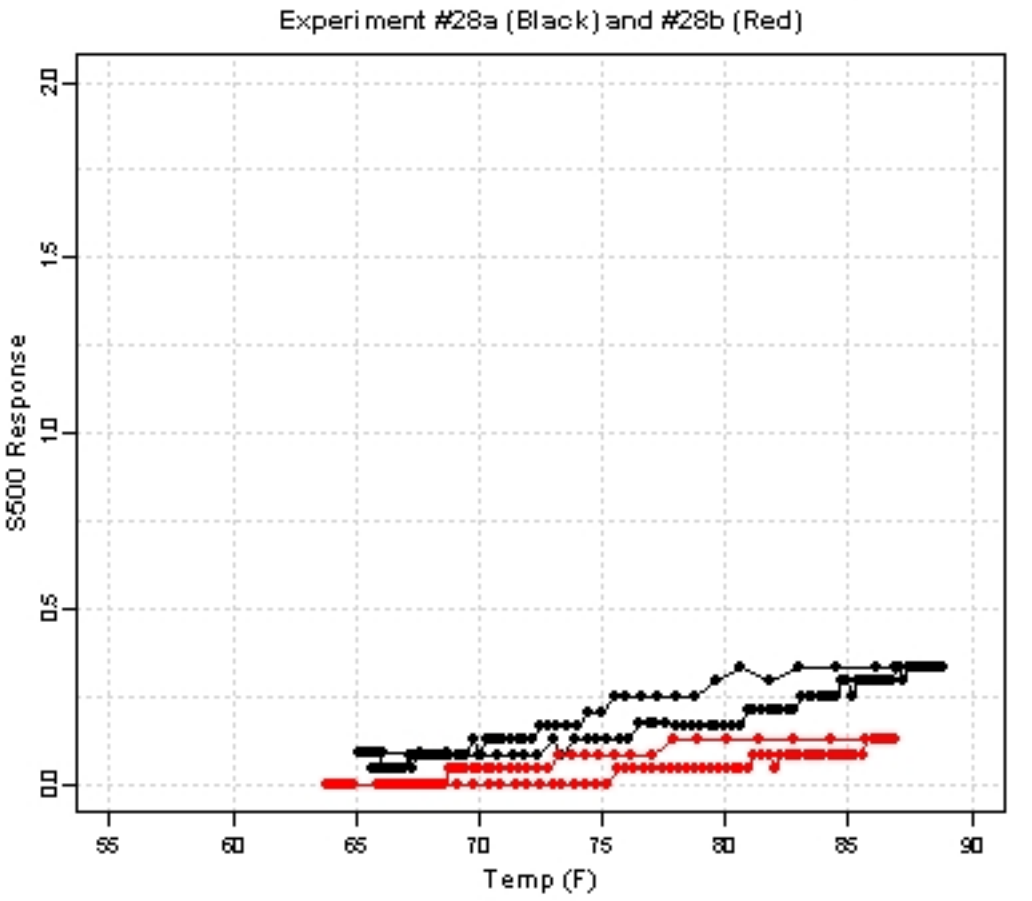
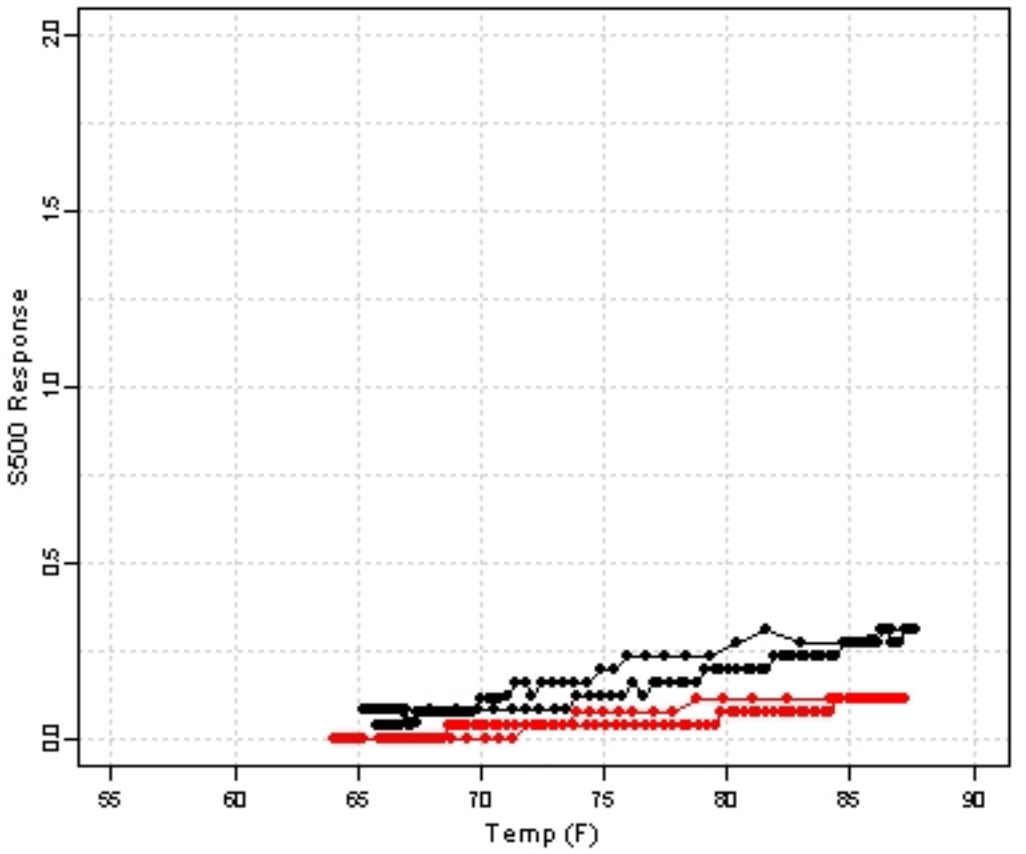
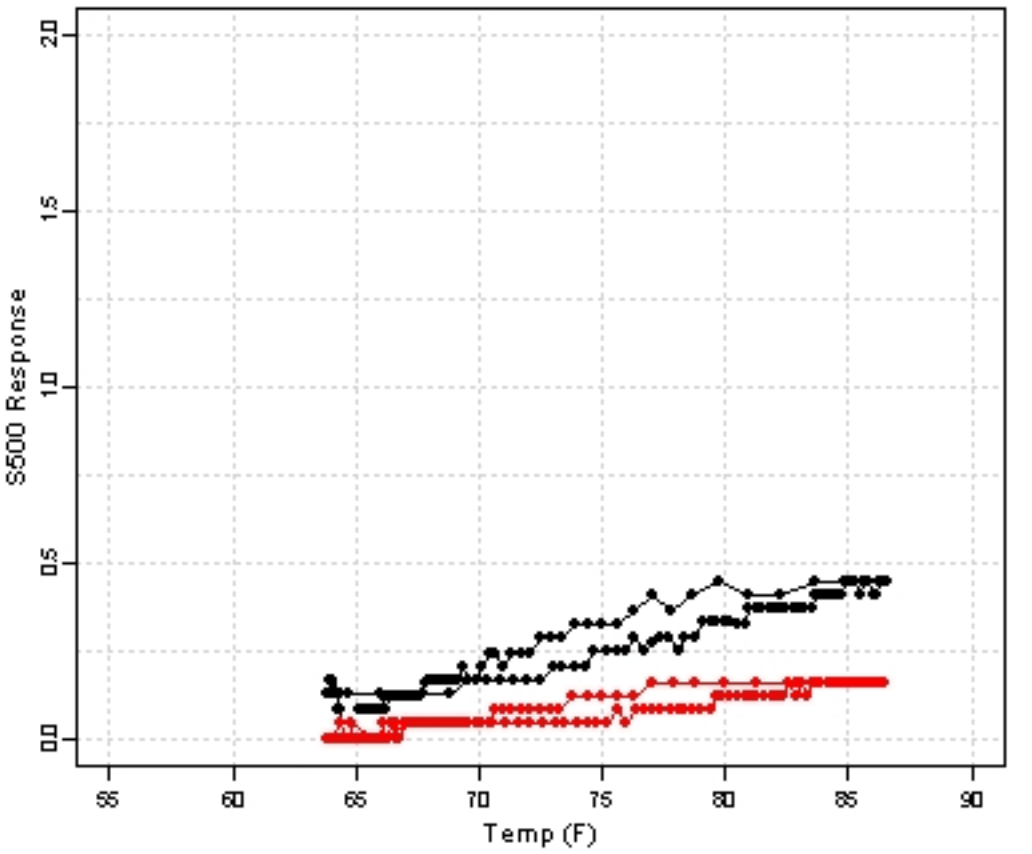


Fig. D38 CO/CO2 Tests: Variable Temperature: S500/48C CO (Expts 27-31)









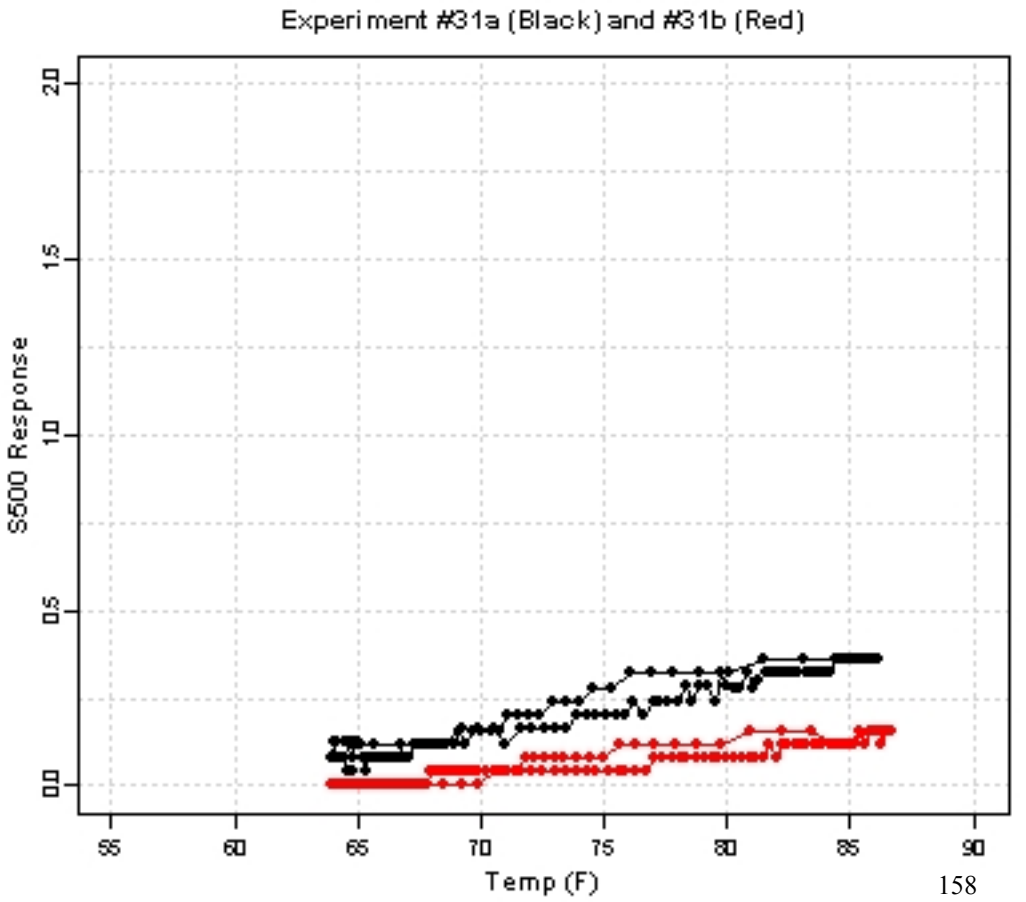
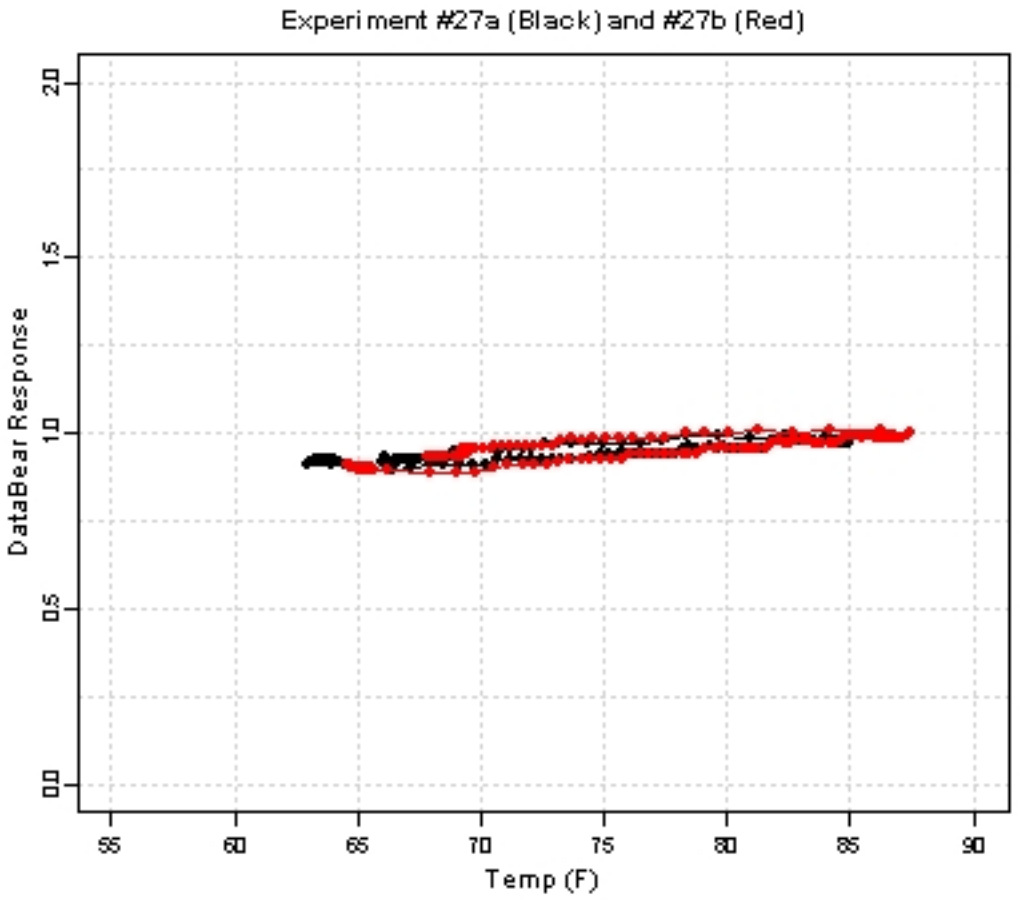
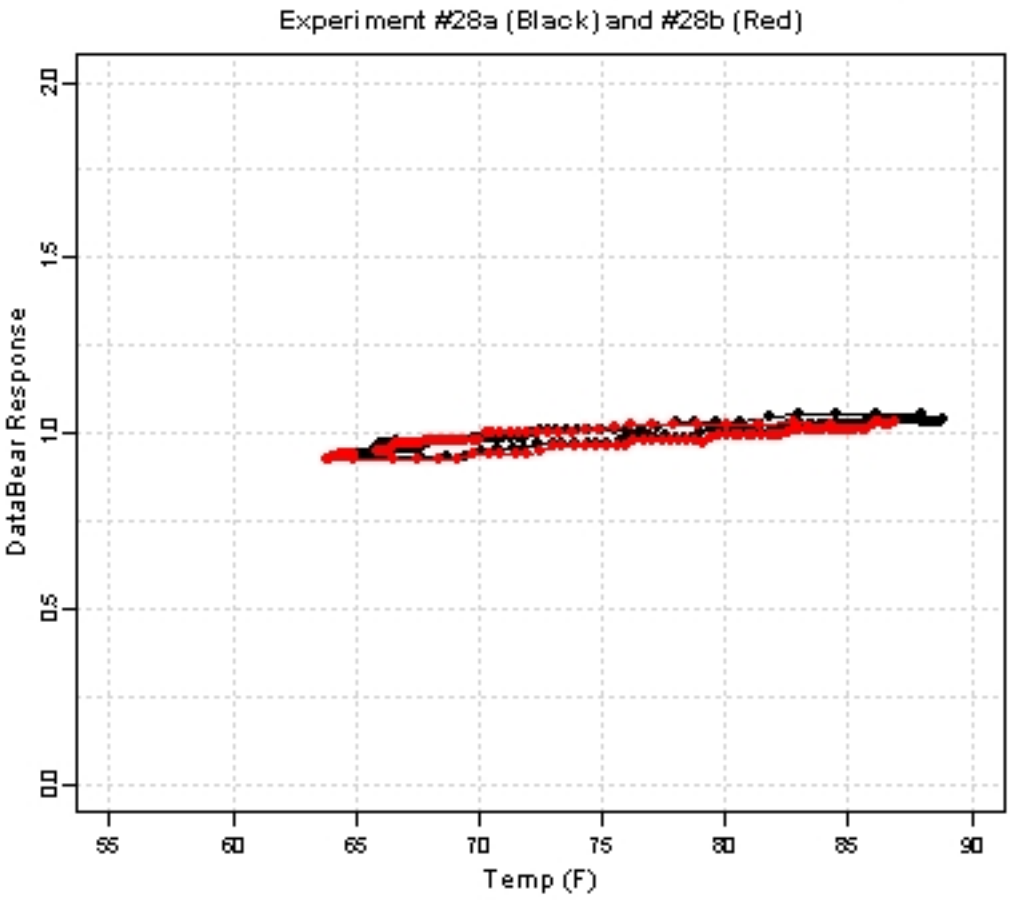
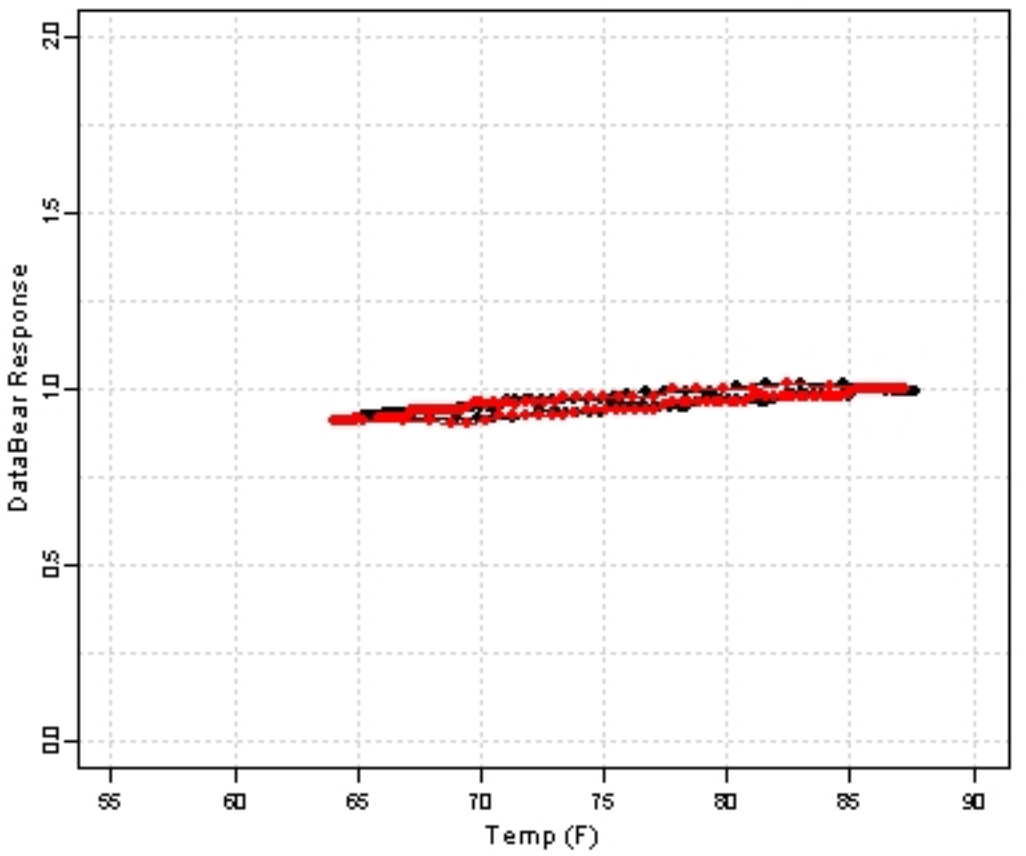
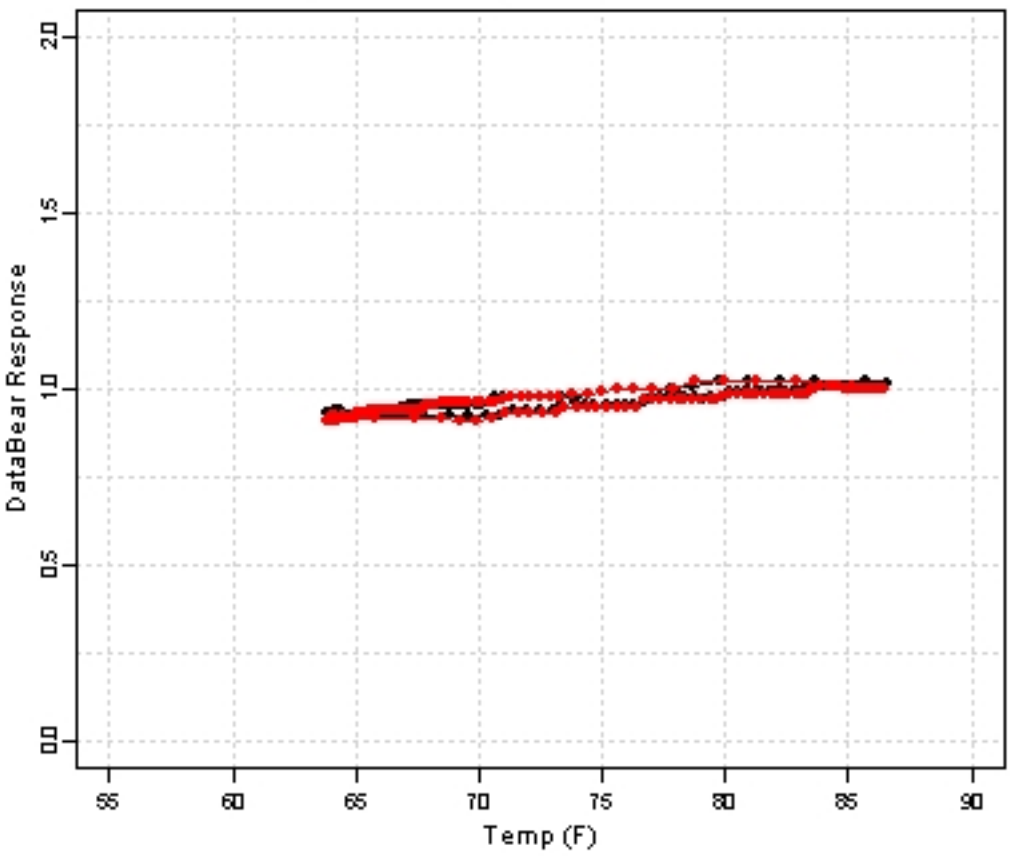


Fig. D39 CO/CO2 Tests: Variable Temperature: DataBear/48C CO (Expts 27-31)









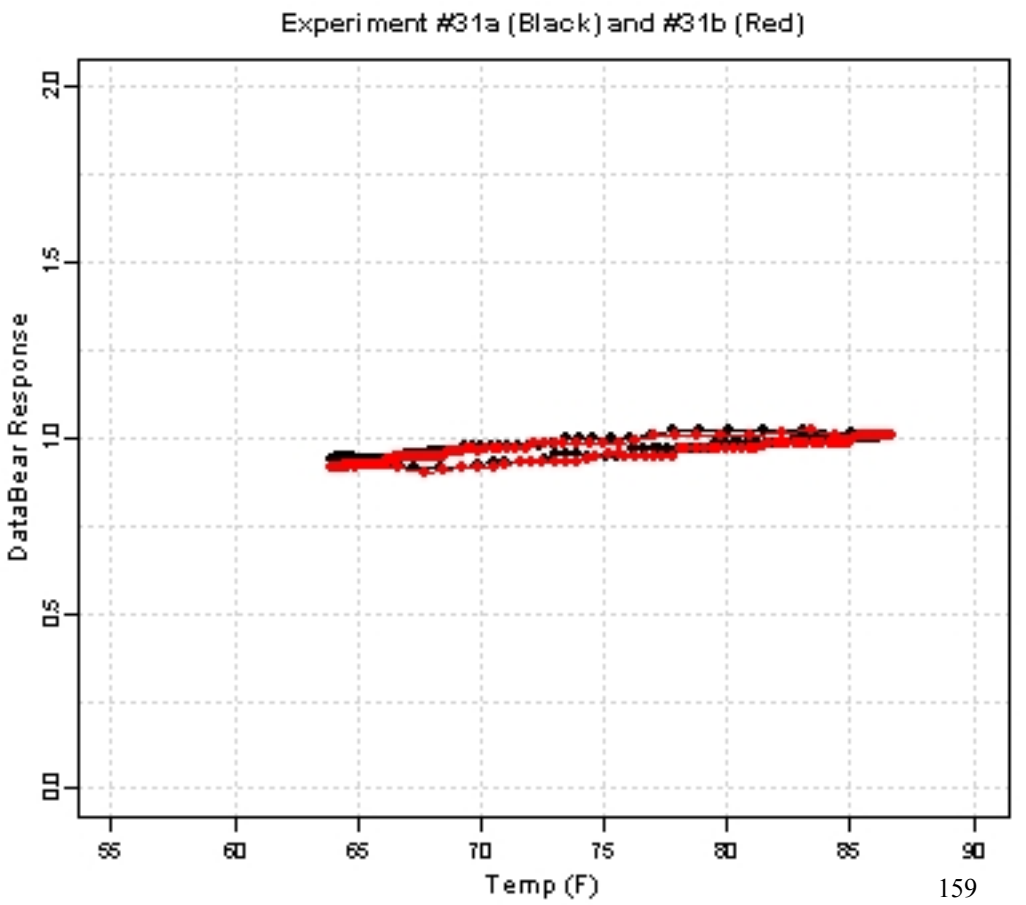
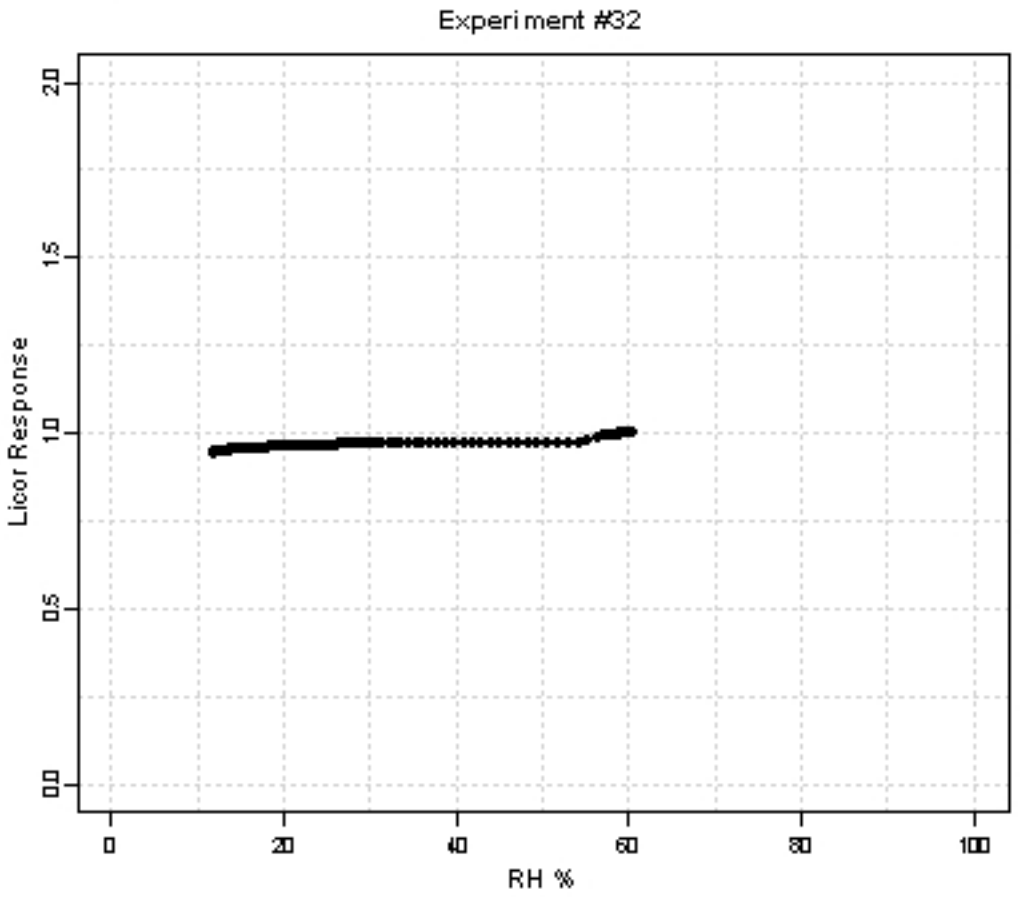
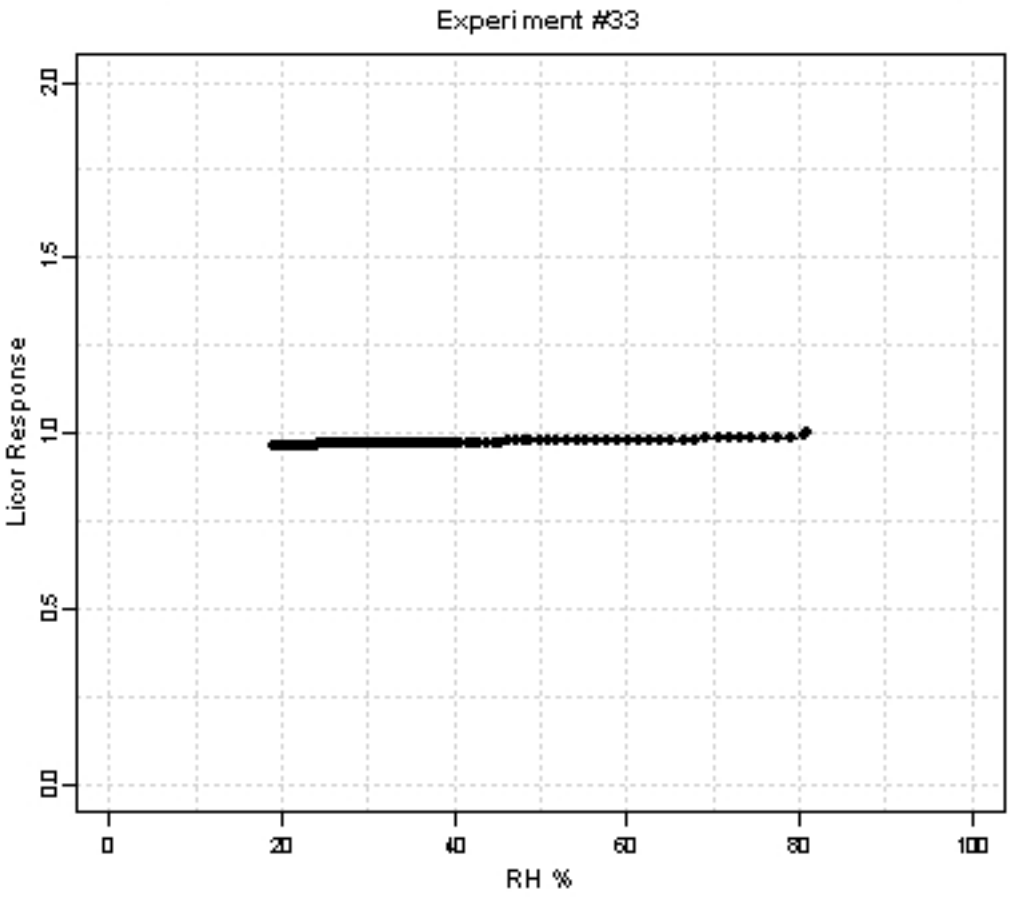


Fig. D40 CO/CO2 Tests: Variable Relative Humidity #1: Licor/Licor CO2 (Expts 32-34)





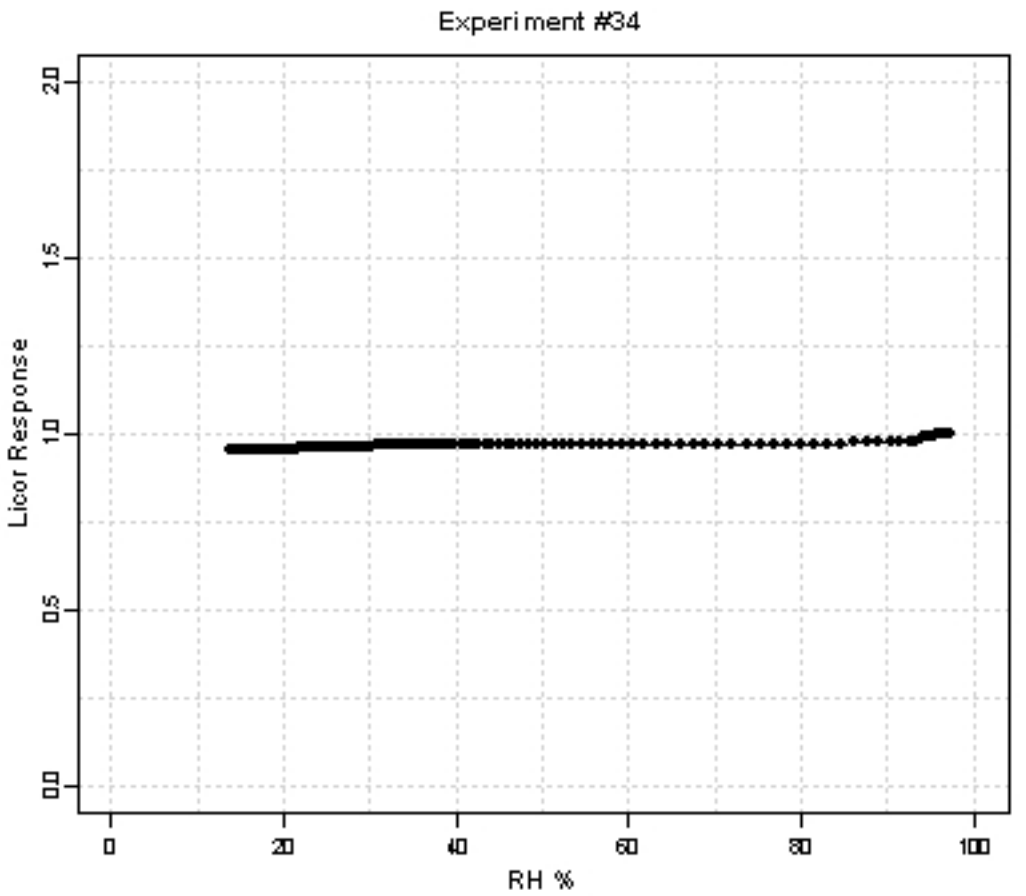
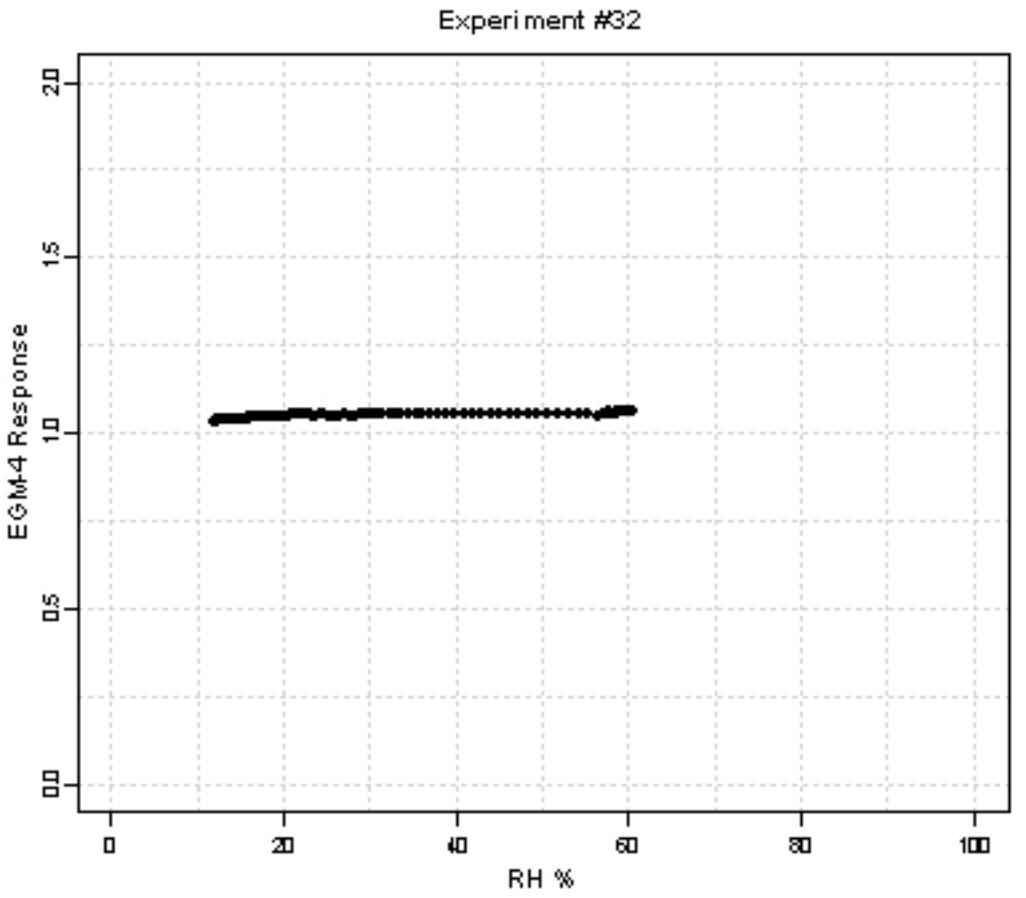
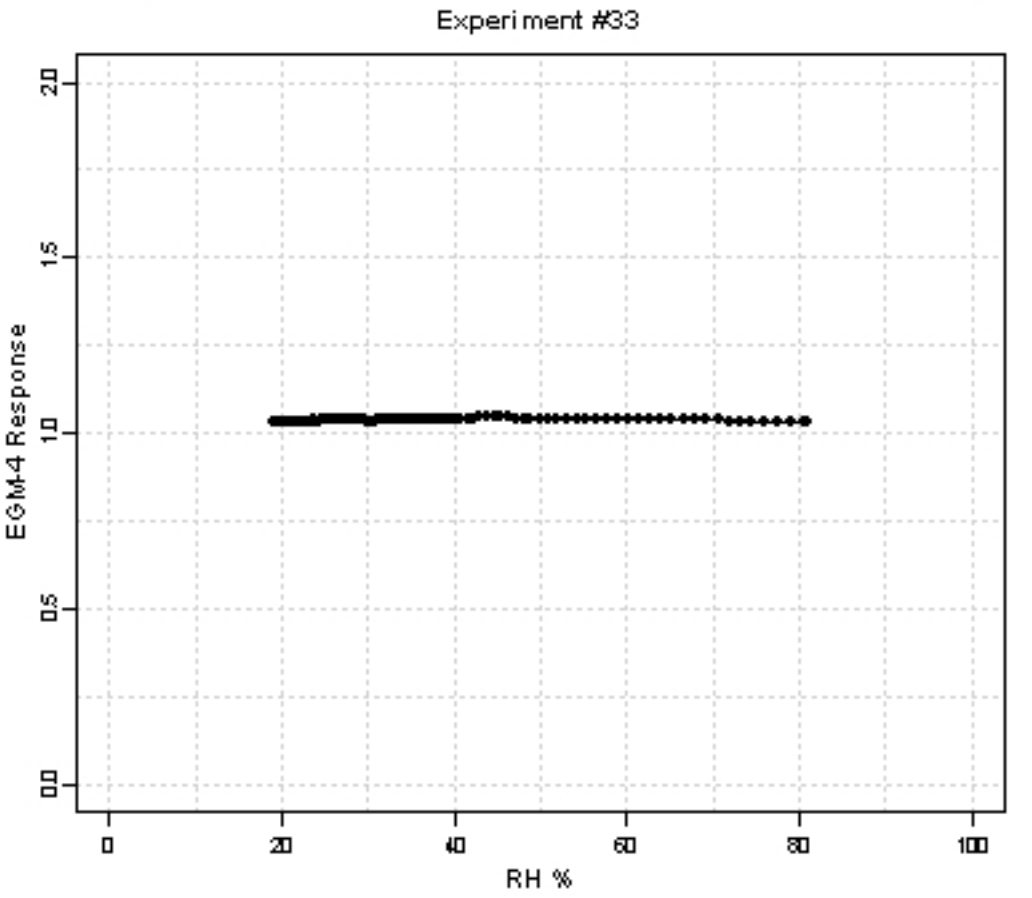


Fig. D41 CO/CO2 Tests: Variable Relative Humidity #1: EGM-4/Licor CO2 (Expts 32-34)





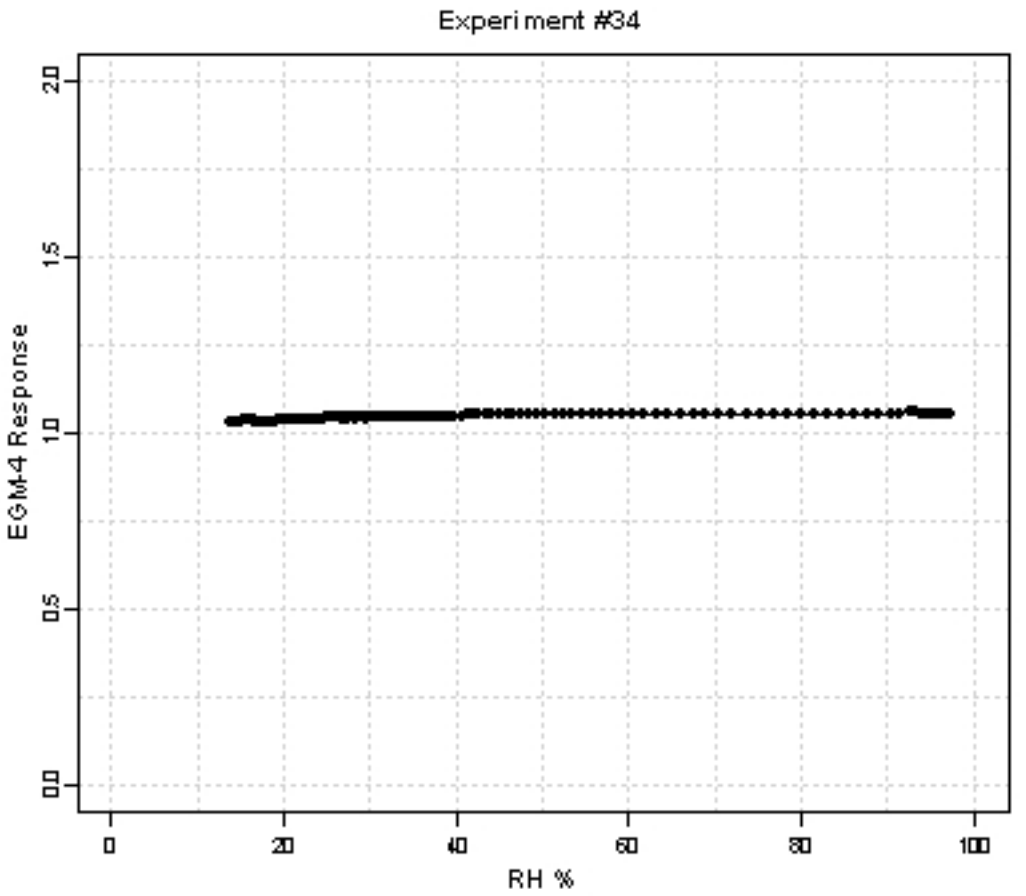
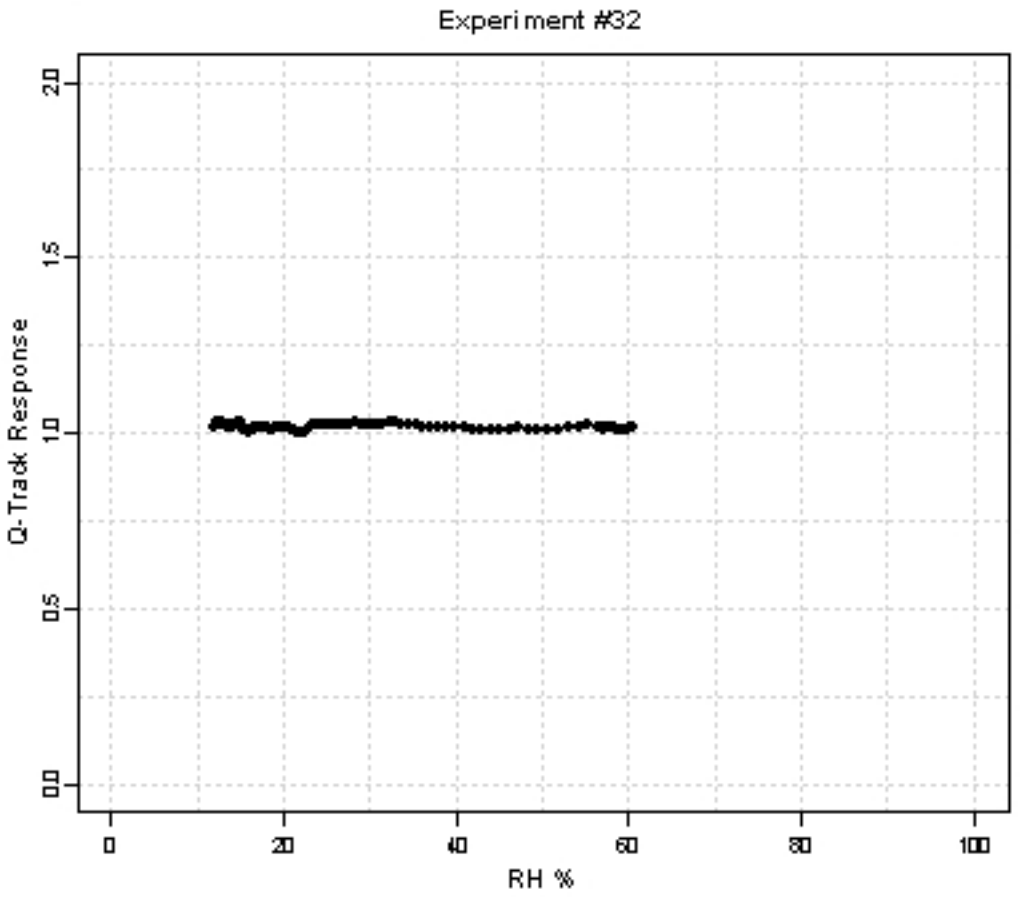
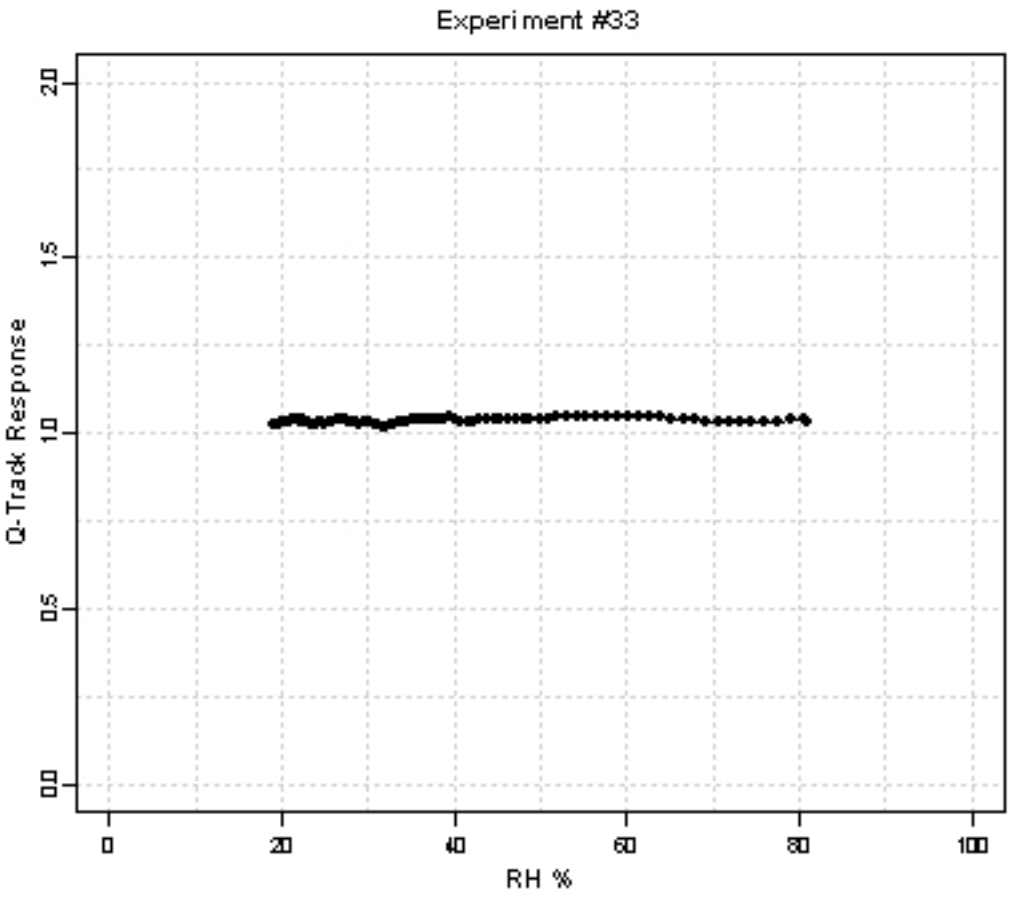


Fig. D42 CO/CO2 Tests: Variable Relative Humidity #1: Q-Track/Licor CO2 (Expts 32-34)





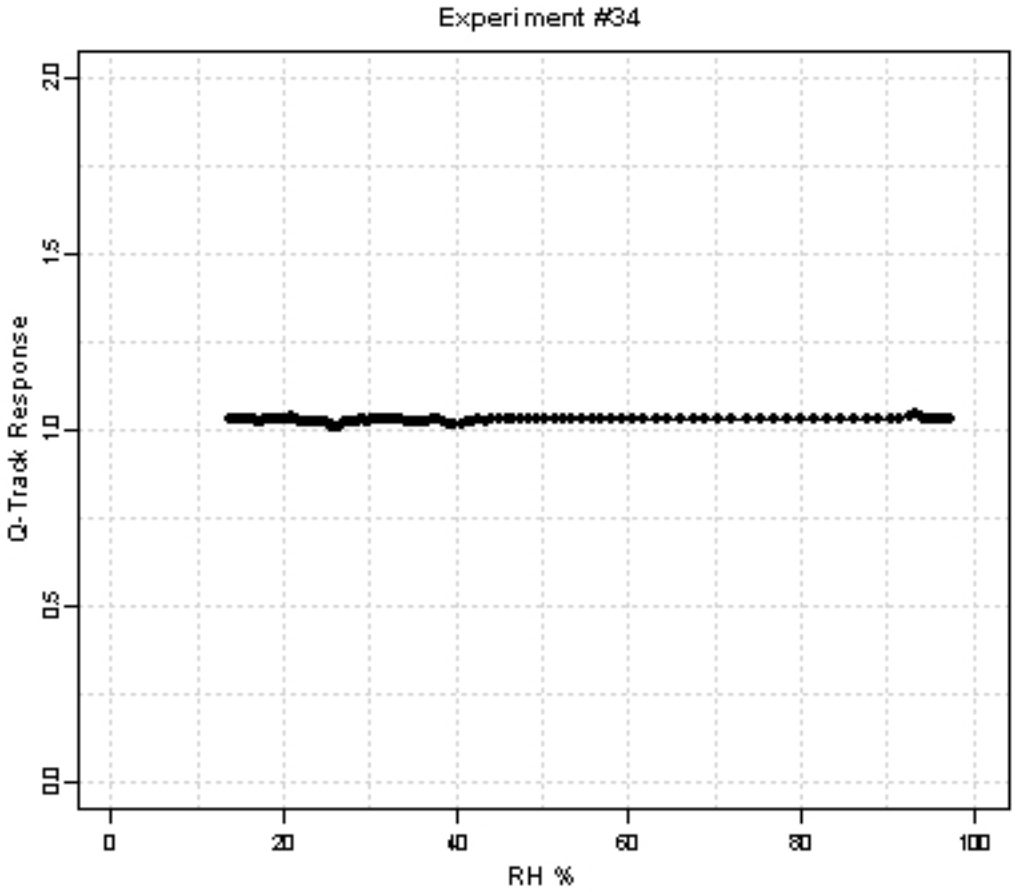
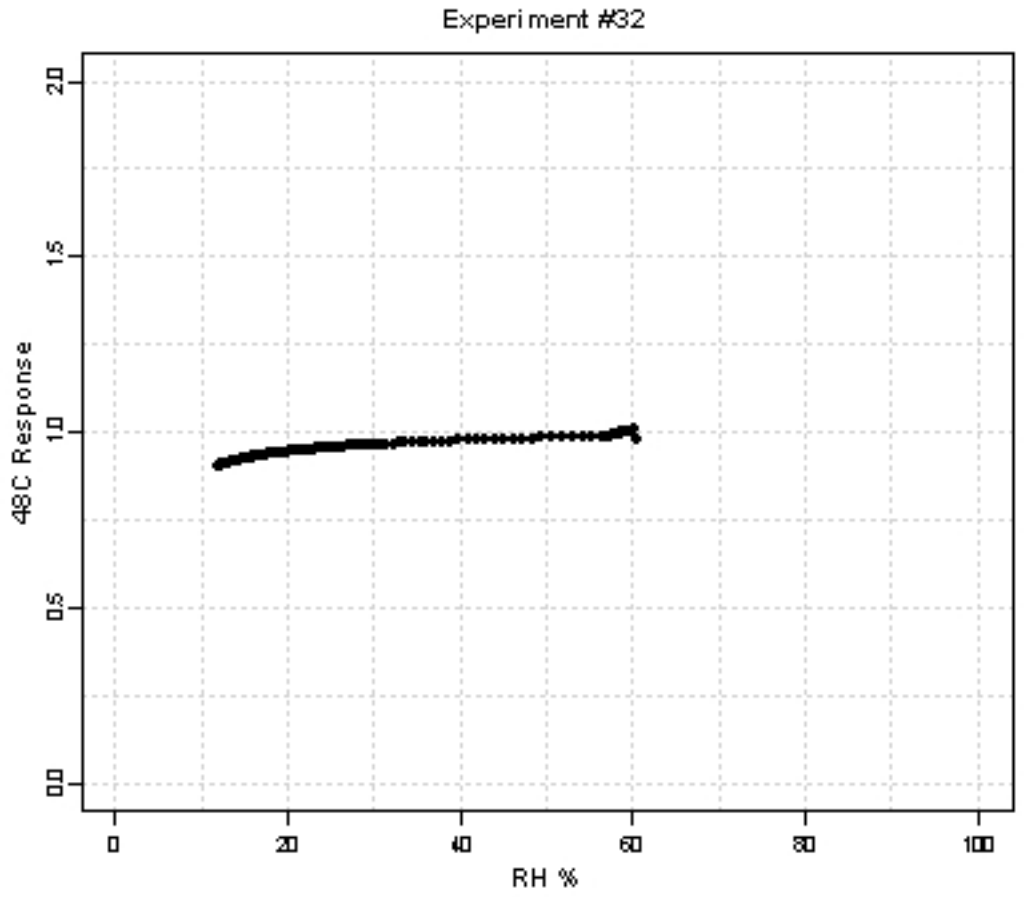
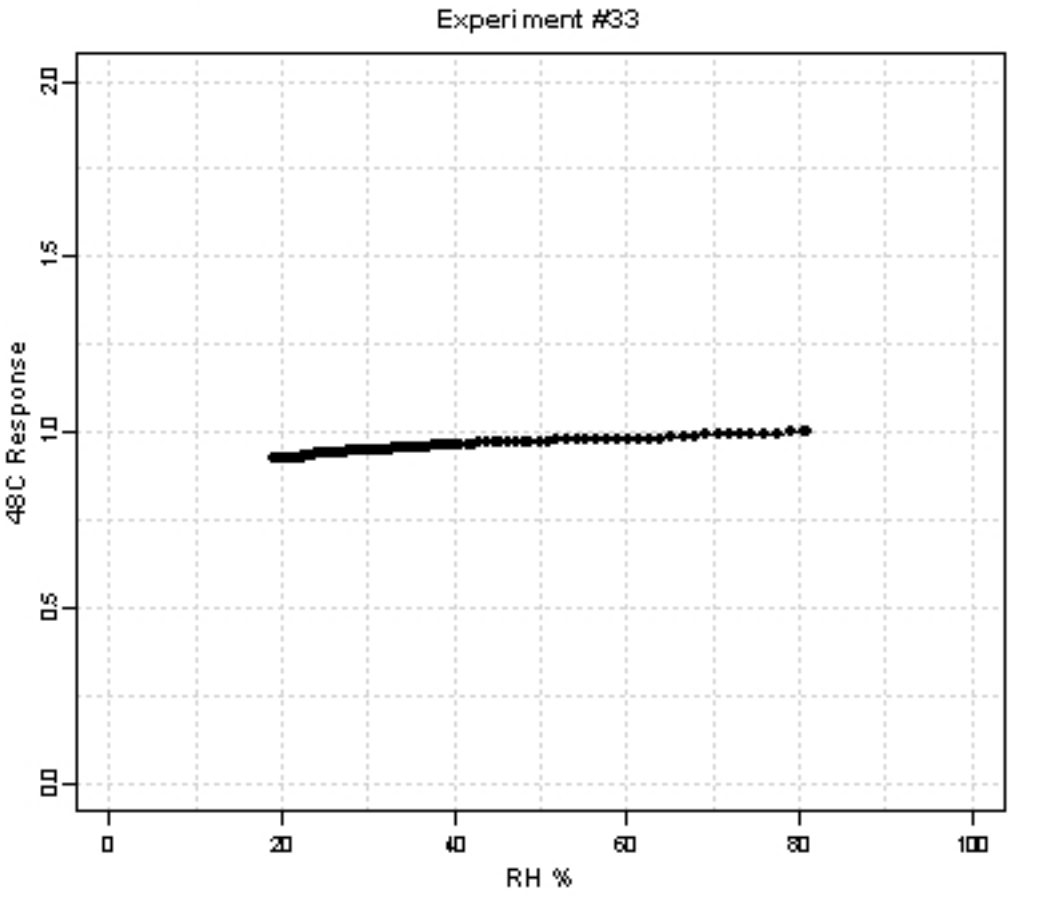


Fig. D43 CO/CO2 Tests: Variable Relative Humidity #1: 48C/48C CO (Expts 32-34)





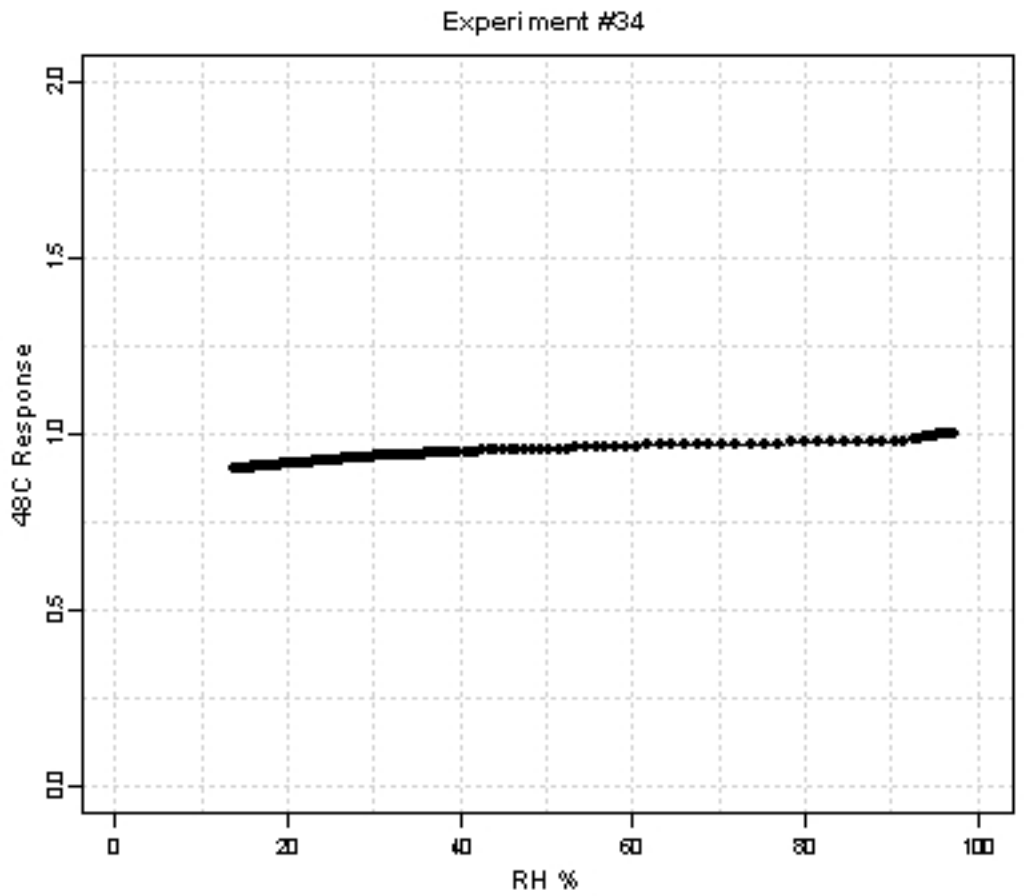


Fig. D44 CO/CO2 Tests: Variable Relative Humidity #1: Q-Track/48C CO (Expts 32-34)