

Experimental analysis of tracer gas injection methods simulating aerosols and their effects on
dispersion in aircraft cabins

by

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Abstract

This thesis focuses on experimental environmental engineering in an wide-body aircraft cabin, utilizing injected tracer gas to simulate aerosol dispersion. In this present study, a Boeing 767 mockup cabin section consisting of 11 rows (7 seats per row in a 2-3-2 configuration) is used as the test environment, with a neutrally-buoyant mixture of helium and carbon dioxide used as the injected tracer gas. A total of 123 injection tests were performed at two separate injection source locations in the cabin, using 3 distinct injection methods. The locations tested were the “center” of the cabin and a wall (window) seat in the same row, while the injection methods were a 1-minute puff injection, a 3-minutes puff injection and a (45 minute) continuous injection. Previous work at the Aircraft Cabin Environmental Research Laboratory (ACERL, or simply ACER) has primarily used the continuous injection method, with some studies using a “coughing” type or puff type injection. For comparison purposes, this present study uses a slightly modified puff injection type along with the continuous types. After evaluation of an initial data set, the focus of the study shifted to evaluating the effect the cabin environment (with its inherent chaotic local air currents) had on the three different injection types.

The data for each injection type for each testing location were compared. It was found that each injection type had different responses. The responses were evaluated both as the carbon dioxide concentrations versus time graphs, as well in reduced form (the fraction measured, or inhaled, versus the total injected, per location). The reduced responses were not just different, but for the three injection types, they demonstrated a consistent difference between the three injection types that was unexpected. An interesting discovery within the data also showed that there was significant variation in the data from test to test, an unrepeatability and unpredictability, which had not been explored in previous work at ACERL. This variation is best

seen in continuous data sets, where shifts in the carbon dioxide concentrations measured at a given location during the injection (a continuous and constant injection) phase change from one quasi-stable steady state condition to a radically different pseudo steady state response. Most previous work relied on testing numerous source locations in the cabin with 3-5 tests per location, as opposed to the approach of this present study, which was 18-22 tests per location, per injection type. This large number allowed better insight into the differences in average behaviors for each injection type, and for insights into the variations in behavior at each injection and measurement location for a given injection type.

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List of Abbreviations

ACER	Informal name for ACERL
ACERL	Aircraft Cabin Environmental Research Laboratory
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CDC	(US) Centers for Disease Control and Prevention
COVID	Coronavirus Disease
DAQ	Data Acquisition (system)
DARPA	(US) Defense Advanced Research Projects Agency
ECS	Environmental Control System
EPA	(US) Environmental Protection Agency
FAA	(US) Federal Aviation Administration
HEPA	High-Efficiency Particulate Air
IBAC	Instantaneous Biological Analyzer and Collector
ISOPASS	Expedient Passenger Isolation System
NI	National Instruments
OSHA	(US) Occupational Safety and Health Administration
PID	Proportional, Integral, Derivative (control)
ppm	parts per million
PSU	Power Supply Unit
PWM	Pulse Width Modulation
SLM	Standard Liters per Minute
TRANSCOM	Informal name of USTRANSCOM
USTRANSCOM	United States Transportation Command

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Dedication

To my mother and my father and my sister. For Nonie.

Chapter 1 - Introduction

Exposure to and transmission of pathogens in any enclosed space are of constant concern, one that requires special attention to details in the environmental engineering of the enclosed space. This is especially true for mass transport, of which aircraft represent a particular problem given their tight spaces, international routes, and sheer traffic daily. In 2019, the US Department of Transportation Bureau of Transportation Statistics indicated that the total number of passengers for that year was 811 million, domestic, and 245 million, international. These passengers traveled on 8.6 million domestic flights, and 1.6 million international (Bureau of Transportation Statistics, 2020).

Passengers during flights are restricted to their seats in an already confined space. Given the length of flights, particularly international ones, there is a high risk of exposure to biological agents. Transmission of infectious particles in aircraft cabins occurs most often through two modes: person-to-person droplet contact and airborne transmission of droplet nuclei. The airborne transmission of droplet nuclei is a main concern, as the very small droplets (aerosols) exhaled during normal respiration or a cough can evaporate quickly, leaving infectious particles to travel freely in local air currents, where they can remain for far longer than when attached to a heavier droplet (Gralton, 2011). The longer they are airborne, the further they can travel from an exposure source.

As such, proper design and evaluation of aircraft air quality through ventilation and purification (through HEPA filters) systems and flow regimes are crucial to maintaining a safe cabin environment. The Aircraft Cabin Environmental Research Laboratory (ACER) at Kansas State University was created to study these issues, utilizing a Boeing 737 cabin section and a Boeing 767 mock-up cabin.

The research presented in this thesis builds upon the previous work done here (see 2.2: Previous ACER Studies) at ACER by (Mahmoud, 2021), (Shehadi, 2015), (Darrah, 2018), (Madden, 2015), and expands on the nature of tracer gas injection methods, how they interact with chaotic local air currents, and ultimately how this affects exposure rate. This present study was originally intended as a validation and comparison to the work done previously at ACER, and to the 2020 study undertaken on behalf of the United States Transportation Command (USTRANSCOM), the Defense Advanced Research Project Agency (DARPA) and the Air Mobility Command (Silcott, et. al., 2020).

This project started as an evaluation of the effects of different injection regimes on carbon dioxide diffusion and the subsequent data reduction to percent relative exposure (see Chapter 5: Data Reduction Techniques). Previous work at ACER had been completed using primarily a continuous injection method, with some “coughing” type injection (shorter, with a higher mass flow rate). This present study took a similar approach using the continuous injection method, but modified the coughing injection to simply be a shorter injection span at the same mass flow rate, the idea being to compare the results of the different injection methods. Shortly after the sets of both were completed and the data analyzed at a single testing location, it was decided to include another injection type with an intermediate duration. This was done as the responses in carbon dioxide concentration vs. time showed highly variable behavior, and it was necessary to investigate if these results were products of the injection types themselves or the cabin environment; an intermediate injection would respond intermediate to the other methods in theory, and this is what was observed. The study pivoted its attention on the underlying effects of the aircraft cabin itself; how the local air currents affect dispersion of tracer gases, and how those local air currents are themselves chaotic. While the work of Shehadi, 2015, was similar, this

present study opted for a more focused approach rather than broad, testing at fewer locations (two), but with many more tests run to capture the behavior of each injection type more fully, per location.

The data for each injection type for each testing location were compared collectively. It was found that each injection type had different responses. The responses here are referring to both the carbon dioxide concentrations vs. time graphs, as well as the reduced data (*percent relative exposure* per location collection site around source) per test. The responses were not just different, but they demonstrated a consistent relationship between the three injection type sets that was unexpected. An interesting discovery within the data also showed that there was significant variation in the data from test to test within each injection type, an unrepeatability, which had not been previously explored in previous work at ACER. This variation is best seen in continuous data sets, where shifts in carbon dioxide concentrations measured over time during the injection phase radically change from a near steady state condition. Most work previously relied on testing numerous source locations in the cabin with 3-5 tests per location, as opposed to the approach of this present study, which was 18-22 tests per location, per injection type. The number of tests conducted allowed better insight into the behaviors of each injection type, and of the cabin's dynamic environment on the level of local air currents.

Chapter 2 - Background

Given the importance of air quality in aircraft cabins, it is necessary to discuss the relation of previous research efforts, especially those of ACER and the TRANSCOM publication, to this present study. It is also necessary to elaborate on the mandates for cabin environmental conditions.

2.1: Aircraft Cabin Air Quality Standards

Passenger aircraft are equipped with environmental control systems (ECS) that monitor and adjust conditions to keep them within official standards, of which for aircraft cabin environments, are set by the Federal Aviation Administration (FAA). A small number of other agencies, notably the Environmental Protection Agency (EPA), the Occupational Safety and Health Administration (OSHA), and the American Society of Heating, Refrigeration, and Airconditioning Engineers (ASHRAE), also have an input in the regulations set.

The FAA does not explicitly set the cabin air temperature and humidity ranges for commercial aircraft, and its only mandate is that the cabin be reasonably comfortable for passengers (Federal Aviation Administration, 2010). ASHRAE does however set the target range for in-flight and also ground conditions at 65°F to 75°F (ASHRAE, 2018). The maximum operating temperatures are also stated and based on whether in-flight infotainment systems are present and/or running. Relative humidity ranges are not explicitly set (ASHRAE, 2018).

Ventilation is one of the most important control regimes for the ECS. Proper flowrates determined by the ECS are based on the flowrate required to remove contaminants (both chemical and biological), flow rate of conditioned air to offset heat production, total flowrate required for circulation, and the flowrate required for cabin pressurization. Modern aircraft operate with about half of the supplied air to the cabin being recirculated after passing through

HEPA filters, and half being fresh air brought in after passing through the compressor stage of the turbine engines.

The FAA sets the minimum fresh air per occupant at $0.283 \text{ m}^3/\text{min}$ ($10 \text{ ft}^3/\text{min}$) at cabin altitude of 2440 m (8000 ft), while ASHRAE recommends a minimum of $0.566 \text{ m}^3/\text{min}$ ($20 \text{ ft}^3/\text{min}$), with at least $0.2125 \text{ m}^3/\text{min}$ ($7.5 \text{ ft}^3/\text{min}$) being fresh air or outside air (ASHRAE, 2018).

2.2: Previous ACER Studies

(Shehadi, 2015) focused on the lateral direction airflow distribution in the 767 mock-up cabin, through both smoke visualization and tracer gas dispersion. The flow visualization results highlight a factor that was heavily investigated in this present study, that of chaotic airflow in 3-dimensional turbulent flow. Shehadi characterizes the flow, using a smoke visualization technique, as highly random. Shehadi also characterizes the transport of tracer gases in the cabin as behaving fairly uniformly in their dispersion (forwards vs backwards) when released from Row 7 Seat D (center seat), but had different behavior at the wall seats.

(Darrah, 2018) performed experimental analysis on a prototype passenger isolation system, called ISOPASS. With the ISOPASS deployed, tracer gas was injected from inside the containment unit and its concentrations measured at various points throughout the cabin. Darrah's findings concluded that the ISOPASS was entirely effective at containing the tracer gas to safe levels. Matching pair tests were conducted with the ISOPASS on/off.

(Madden, 2015) focused on the effects of passenger loading (thermal and physical) and ventilation air on airflow patterns in the aircraft cabin. Madden's findings indicated that passenger loading has a marked effect on airflow patterns.

2.3: Foundations

There are two studies that most heavily influenced this present study and its direction.

(Mahmoud, 2021) researched the dispersion, and containment solutions of possibly infections aerosols in aircraft cabins, including continued work on the previously mentioned ISOPASS system. Mahmoud's work served as a foundation to base this present study around, including the placement of sampling ports around the source and the tested source locations, and in particular the use of different injection techniques (continuous and cough). The coughing injection technique utilized by Mahmoud was adopted and modified for the purposes of this present study, and expanded upon to include an in between cough, which was done to better understand the relationship between continuous and coughing injection types. It was modified to be injected longer and at a lower volume flow rate so as to impart less momentum into the injected tracer gas (Mahmoud used 1 second injections at a higher peak flowrate).

Much like the work of Shehadi, Mahmoud's research was comprehensive in the testing of multiple locations in the cabin and quantifying the radial (longitudinal and lateral and in between directions) dispersion patterns observed around each tested location. His results showed that contaminant transport patterns are dominated by the cabin airflow pattern in the near field and by distance in the far field.

This present study focused on quantifying linear (longitudinal only, in the forward and rearward directions) dispersion patterns, in greater testing frequency at fewer locations. After initial trials, and comparison to Mahmoud's results (the carbon dioxide concentrations versus-time at locations around the source – for explanation, see 6.2: Typical Responses), the question was raised as to whether the observed variability in the responses over time in both studies was

due to the nature of the injection methods themselves, or if they were being influenced by the cabin environment.

For context on Mahmoud's findings, an explanation is warranted for his results in terms of response graphs; his response graphs are presented in a different format than those of this present study. The blue line represents the carbon dioxide sampled concentration at the source and is not of immediate interest. The sensor (for the source) saturated at 2000 ppm and does so for most of the test. Of interest, however, are the orange and grey lines. Looking at Figure 2.1, the orange line represents the carbon dioxide concentration at position A2, which is 0.84 meters from the source in the opposite direction to that of the orientation of the sampling tree (Figure 3.24). The grey line represents the carbon dioxide concentration for the sampling tree, which has 4 ports spaced equidistant to each other by 0.84 meters. The port being sampled from (on the tree) is variable, and changes every 30 minutes. The port being sampled nearest the source is of particular importance, and is denoted as the last quarter of the injection period in Figure 2.2 and the first quarter of injection in Figure 2.3 (quarters are denoted by black division lines). At positions closest to the source (A2 and 0.84 position of the tree) the measured carbon dioxide concentrations are the most chaotic, that is, these positions show the most variation in concentration in ppm over the length of the tests. For Figure 2.2, the sampling tree's nearest port shows a distinct peak and trough behavior. The A2 position, which shows the CO₂ concentration over the entire test duration, shows a behavior of a few 10–15-minute period of high concentration, juxtaposed by long (~30 minute) periods of much lower concentrations. There is no recurring pattern observed. For Figure 2.3 which is the second test of the matching pair, it can be seen that the response is entirely different, even between tests of the same configuration. There is some drift in the response over time, but the response is not marked by peaks and

valleys as in the first test. This is another form of the variation being investigated by this present study.

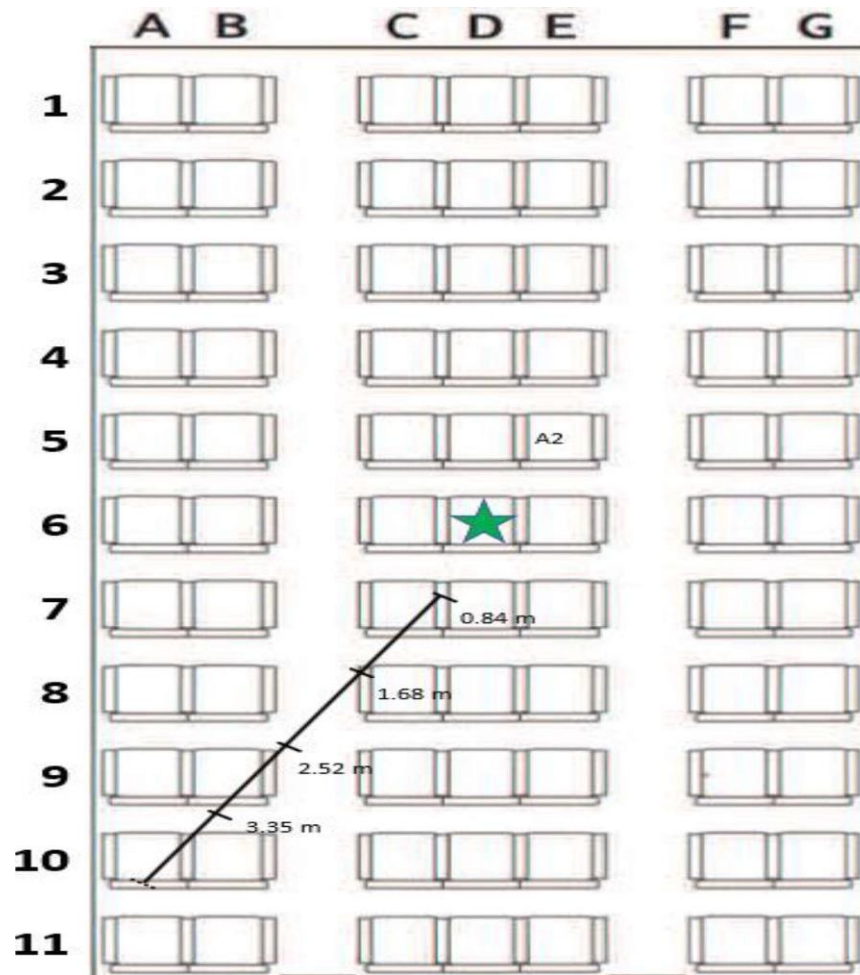


Figure 2.1: (Mahmoud, 2021) Test 7 Setup

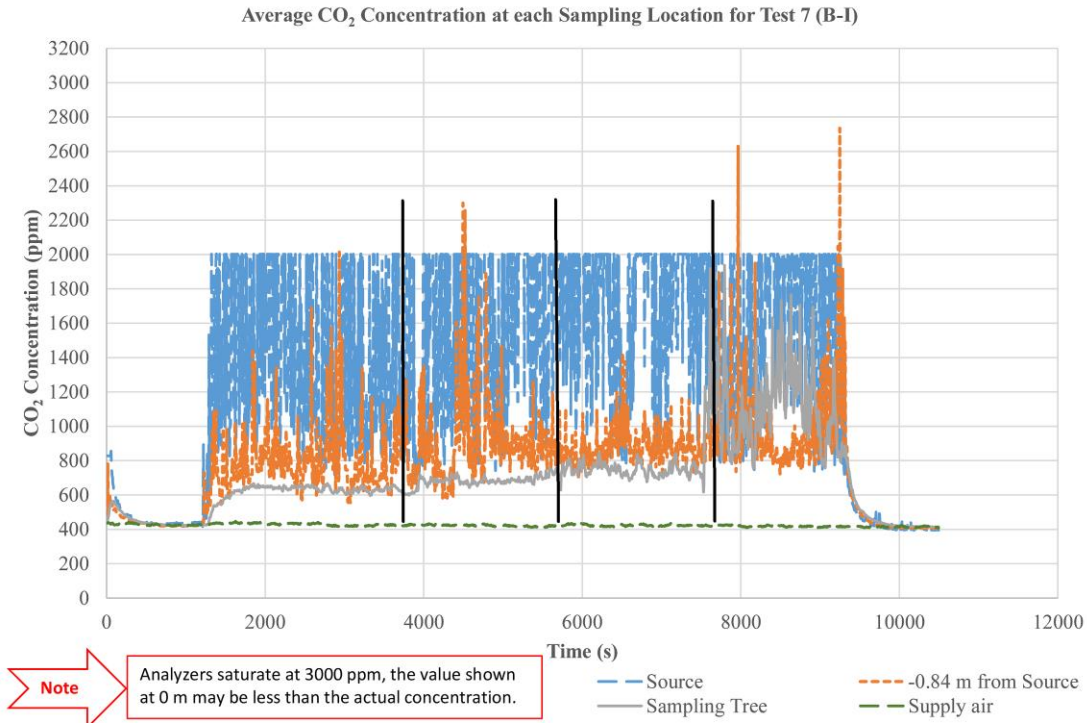


Figure 2.2: (Mahmoud, 2021) Test 7

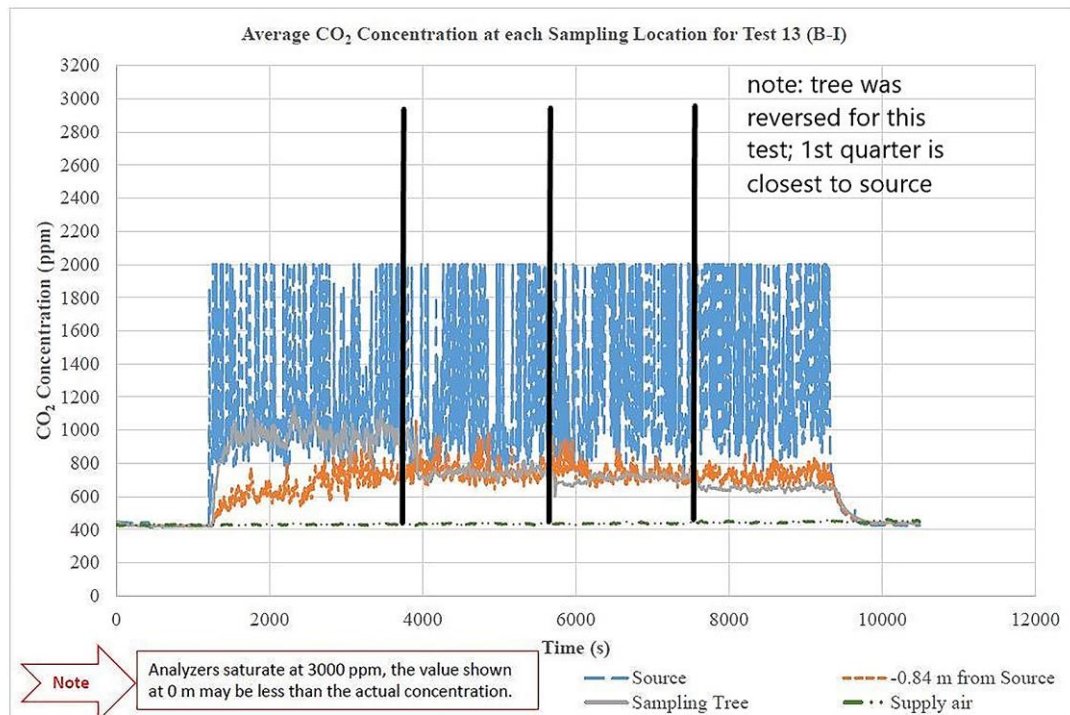


Figure 2.3: (Mahmoud, 2021) Test 13

(Silcott, et. al., 2020) conducted a study in response to the COVID-19 pandemic to investigate aerosol dispersion in aircraft cabins (tests performed on a Boeing 767 and 777 models), with the purpose of determining the risk of exposure in an aircraft cabin. The study utilized fluorescent aerosol tracers and DNA-tagged tracers injected through a mannequin head (injection port is the mannequin's lips). Dispersion was measured using 42 Instantaneous Biological Analyzer and Collector (IBAC) units. Two complete airframe tests were conducted over the course of 8 days, with two days reserved for ground testing and two days reserved for in-flight testing per airframe. While the study utilized fluorescent aerosol tracers and DNA-tagged tracers (not tracer gases, but true aerosols), their methodologies were instrumental in devising this present study to investigate whether the results coming from studies at ACER lab were in-line with theirs. The tracer gas techniques are a cheaper and easier to use alternative for simulating true respiration aerosols.

The findings of this present study found that the rapid mixing, dilution, and removal (through the high air exchange rate of the cabin and recirculation through HEPA filters) limit exposure risk in the tested airframes. In a nearby seat, the maximum exposure equated to just 0.3% of the particles released for an aerosolized source.

The question arose as to whether ACER's testing methodologies could reproduce TRANSCOM's findings, not only for purpose of cross-validation, but also for the justification of the use of tracer gases as an effective simulator of true aerosols. Given the extensive amount of data collected over the years at ACER, this is an important question to ask.

Chapter 3 - Experimental Setup

The Aircraft Cabin Environmental Research (ACER) Lab at Kansas State University houses the Boeing 767 cabin mockup that all testing was conducted in. The mock cabin is an 11-row section housed inside a wooden enclosure, making the entire structure a plenum-type assembly. Inlet air temperature, humidity and flow rate are all controlled electronically to Boeing 767 design in-flight environmental conditions. All seats in the cabin are occupied by mannequins, unless occupied by the tracer gas injection and sampling equipment (select seats). Detailed descriptions of cabin layout and equipment are given in the next sections. For further detail, please see (Mahmoud, 2021, Madden, 2015, Trupka, 2011)

3.1: Cabin Facility

The mock cabin, as mentioned prior, is a plenum enclosure. The entire enclosure measures 7.4 x 9.8 x 4.9 m. East and west hallways flank the long sides of the enclosure, providing access to the diffuser air duct system above and also space for the tracer gas mass flow controllers and analyzers. There are two entrances to the cabin on the north side, one for each aisle in the cabin. A top-down diagram of the cabin and enclosure are shown in Figure 3.1. An important note to make is the seating arrangement inside the cabin, shown in Figure 3.2, of which will be referenced for all tests and results throughout this thesis.



Figure 3.1: ACER Facility

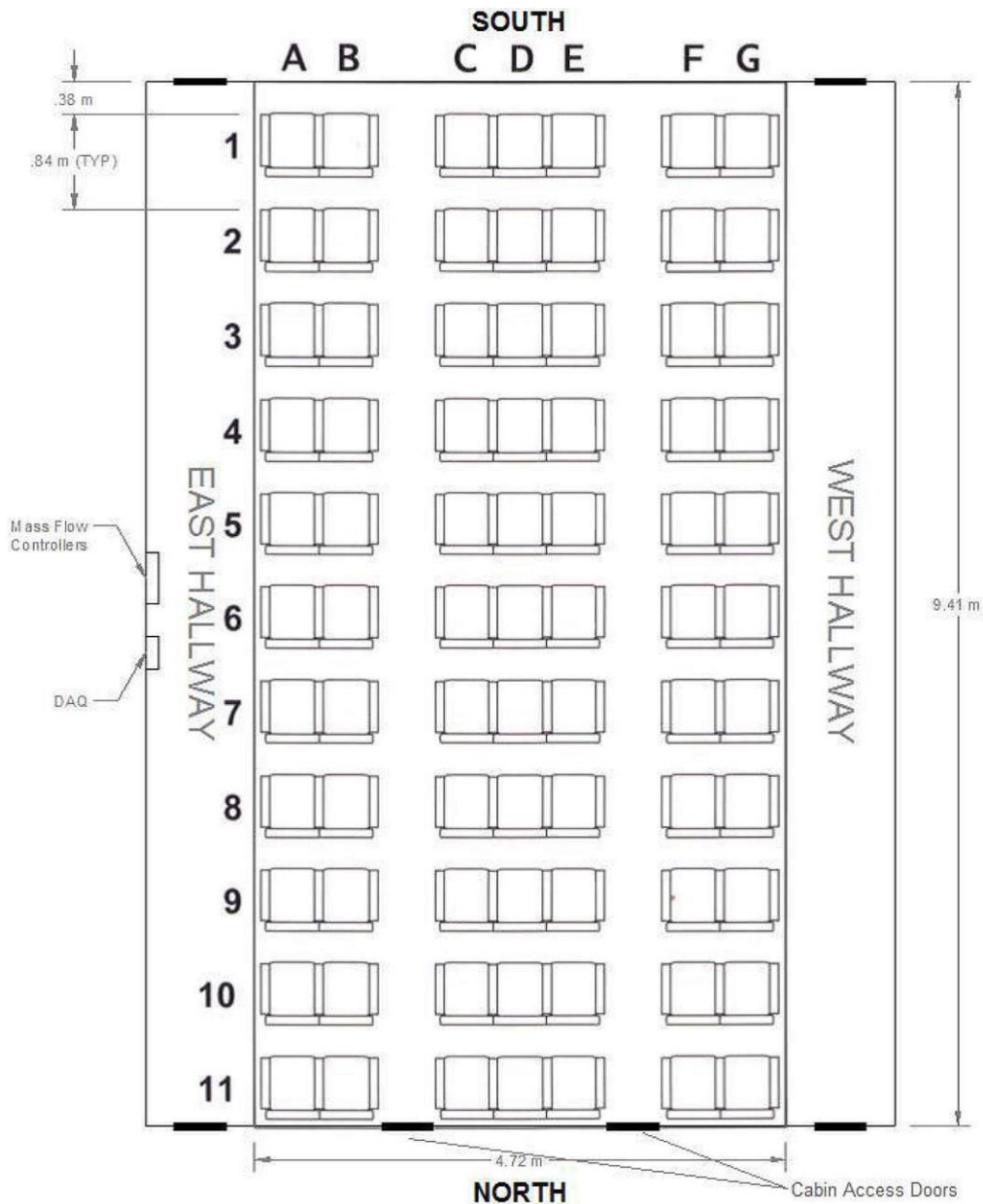


Figure 3.2: 767 Section Seat Arrangement

Shown in Figure 3.3, are the cabin supports, in between of which are the cabin air exhaust gaps. These gaps run along the entire length of the cabin on both sides at floor level. Inlet air enters from the linear diffuser in the ceiling of the cabin, where it is then circulated and

then expelled through the exhaust gaps into the east and west hallways, shown in Figure 3.4. From the hallways it is drawn out by the exterior exhaust fans.



Figure 3.3: Support Columns and Exhaust Gaps

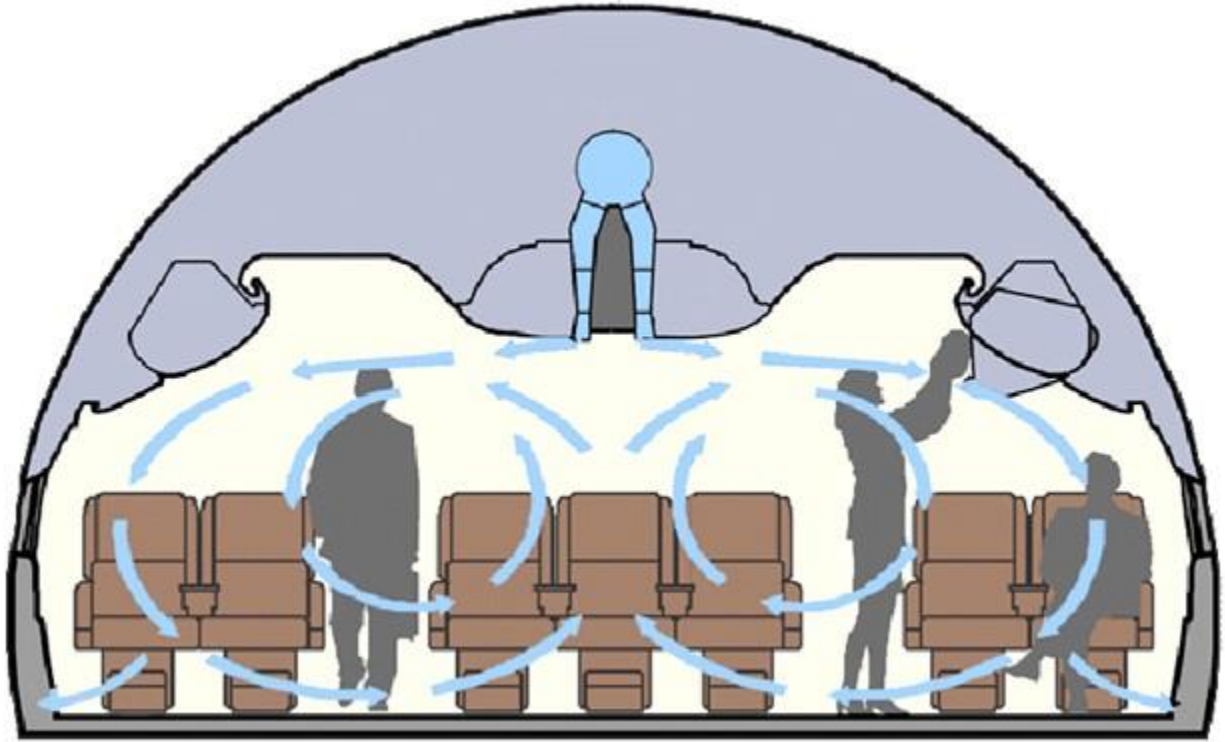


Figure 3.4: Cabin Lateral Circulation (Trupka, 2011)

3.1.1: Cabin Dimensions

The mock-up cabin was designed to simulate a section of a Boeing 767 as faithfully as possible. The walls (shell structure) of the cabin, including the ceiling, are constructed of aluminum sheets. The designed cross-sectional view is shown here in Figure 3.5, reproduced from (Trupka, 2011).

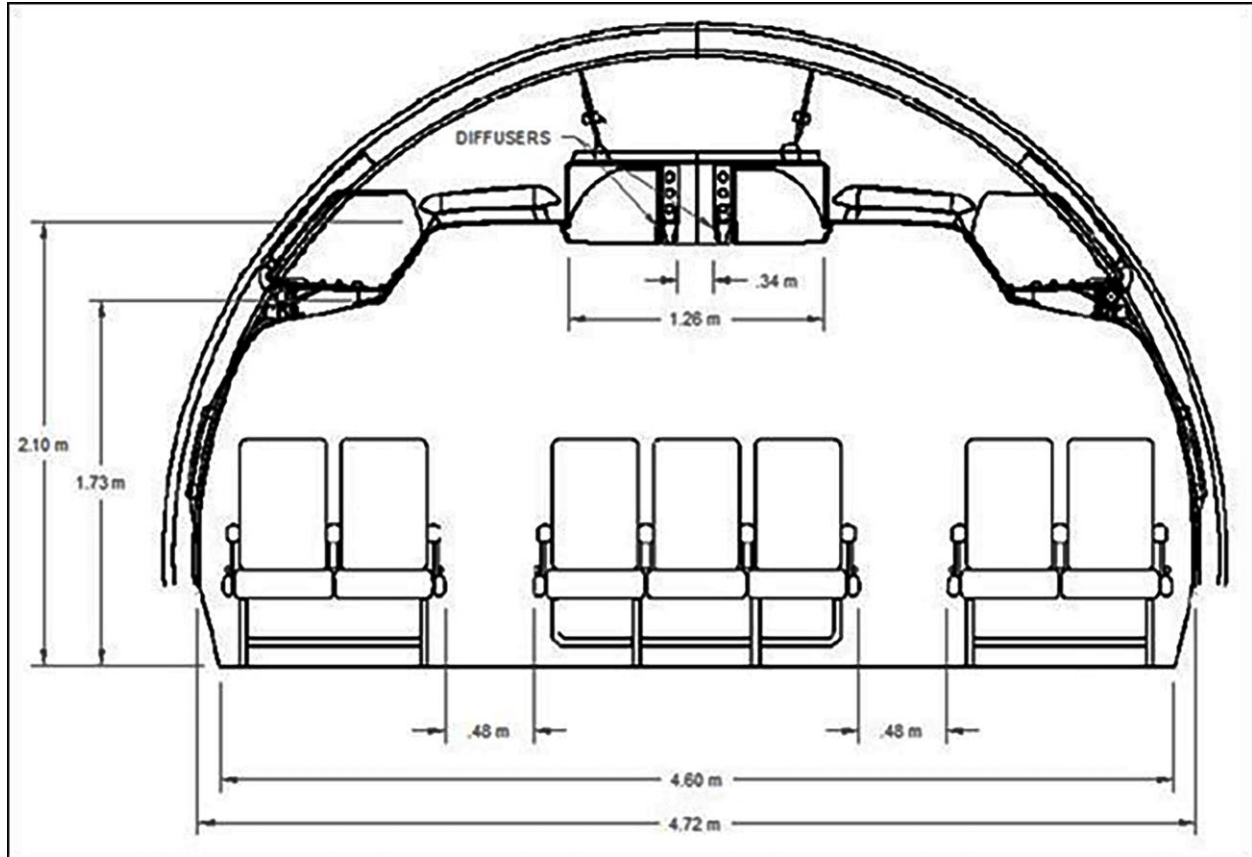


Figure 3.5: Cabin Cross Section Dimensions (Trupka, 2011)

3.1.2: Seat Geometry

There are seven seats per row and 11 rows in the 767 cabin section, giving a total of 77 seats in the mock-up. All seats are original specification, salvaged 767 economy section seats. Boeing 767 economy sections are arranged in a 2-3-2 configuration, and the ACER facility is arranged as such. The dimensions (width and height) of these double and triple seat combinations are given in Figure 3.6 and Figure 3.7, respectively, while Figure 3.8 gives the depth and height dimensions. All figures here are taken directly from (Trupka, 2011).

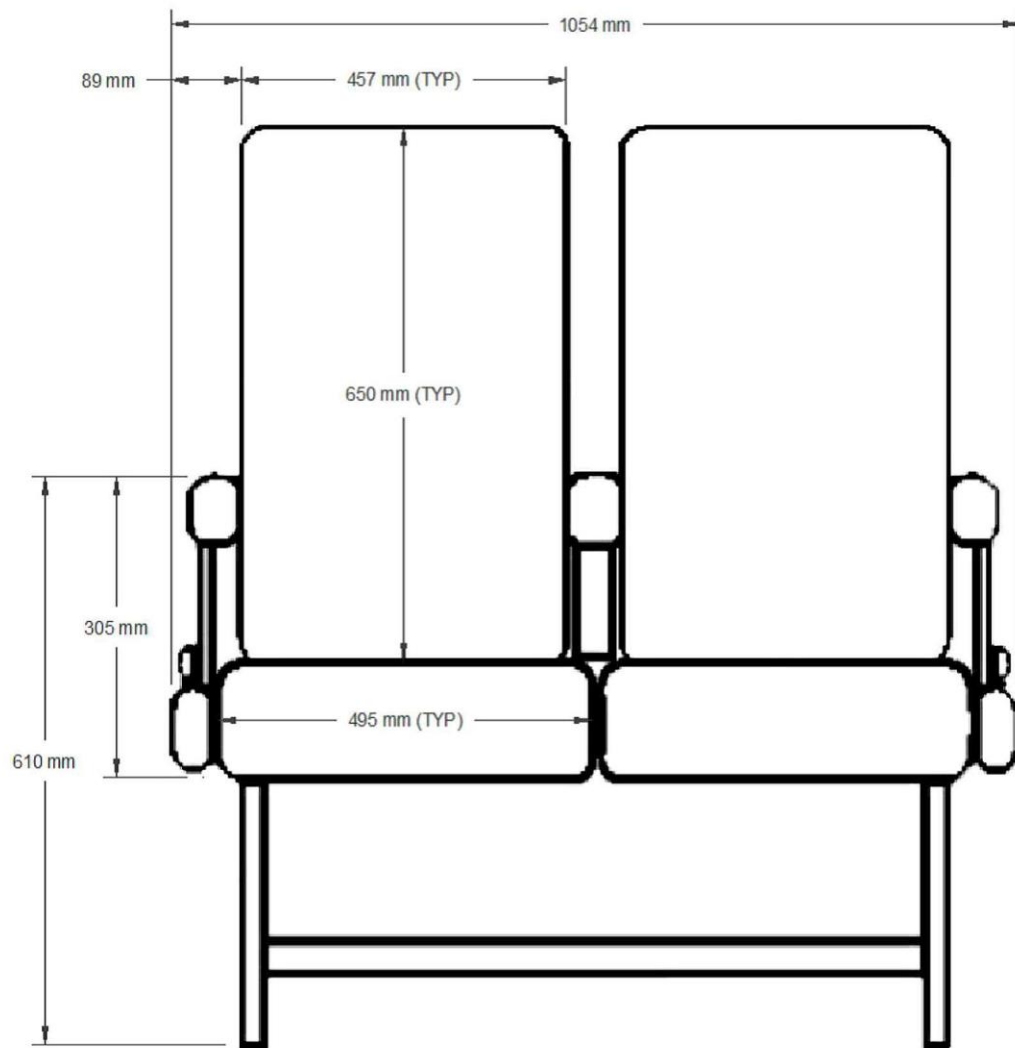


Figure 3.6: Double Seat Dimensions (Trupka, 2011)

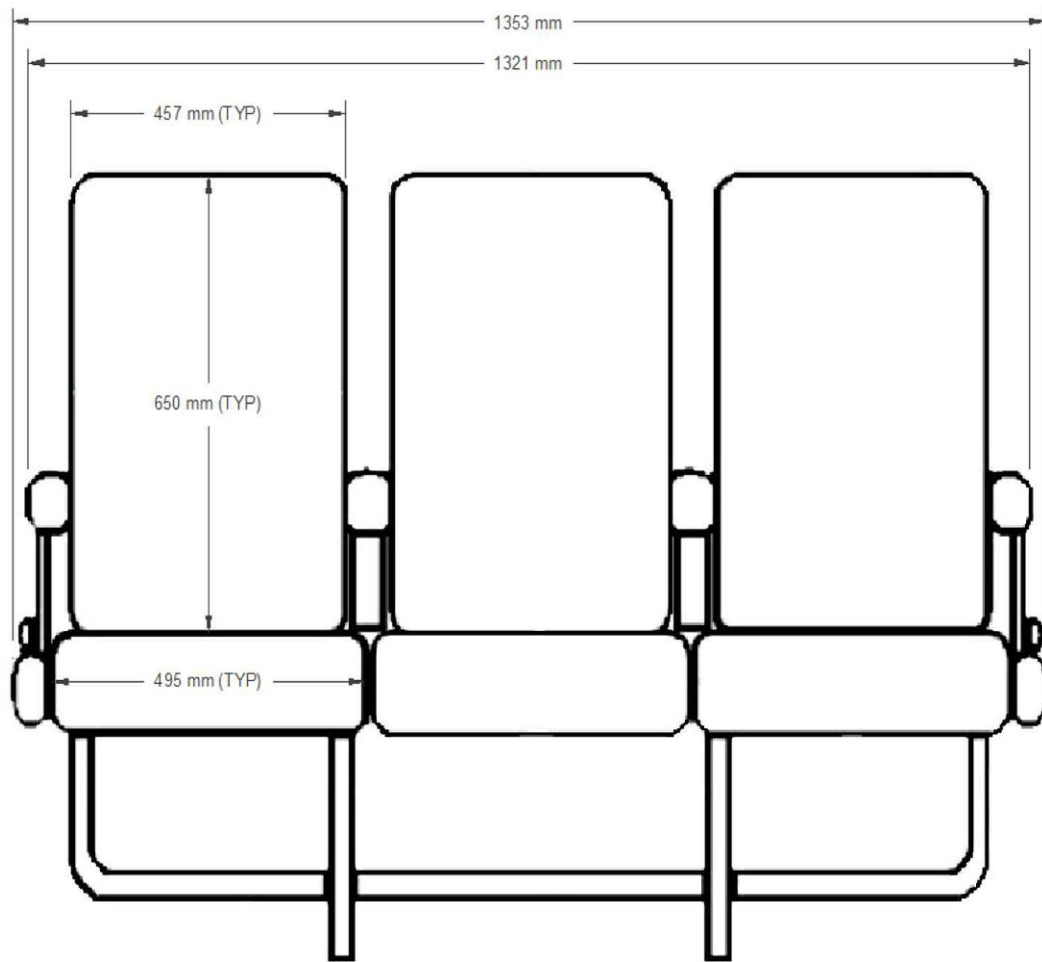


Figure 3.7: Triple Seat Dimensions (Trupka, 2011)

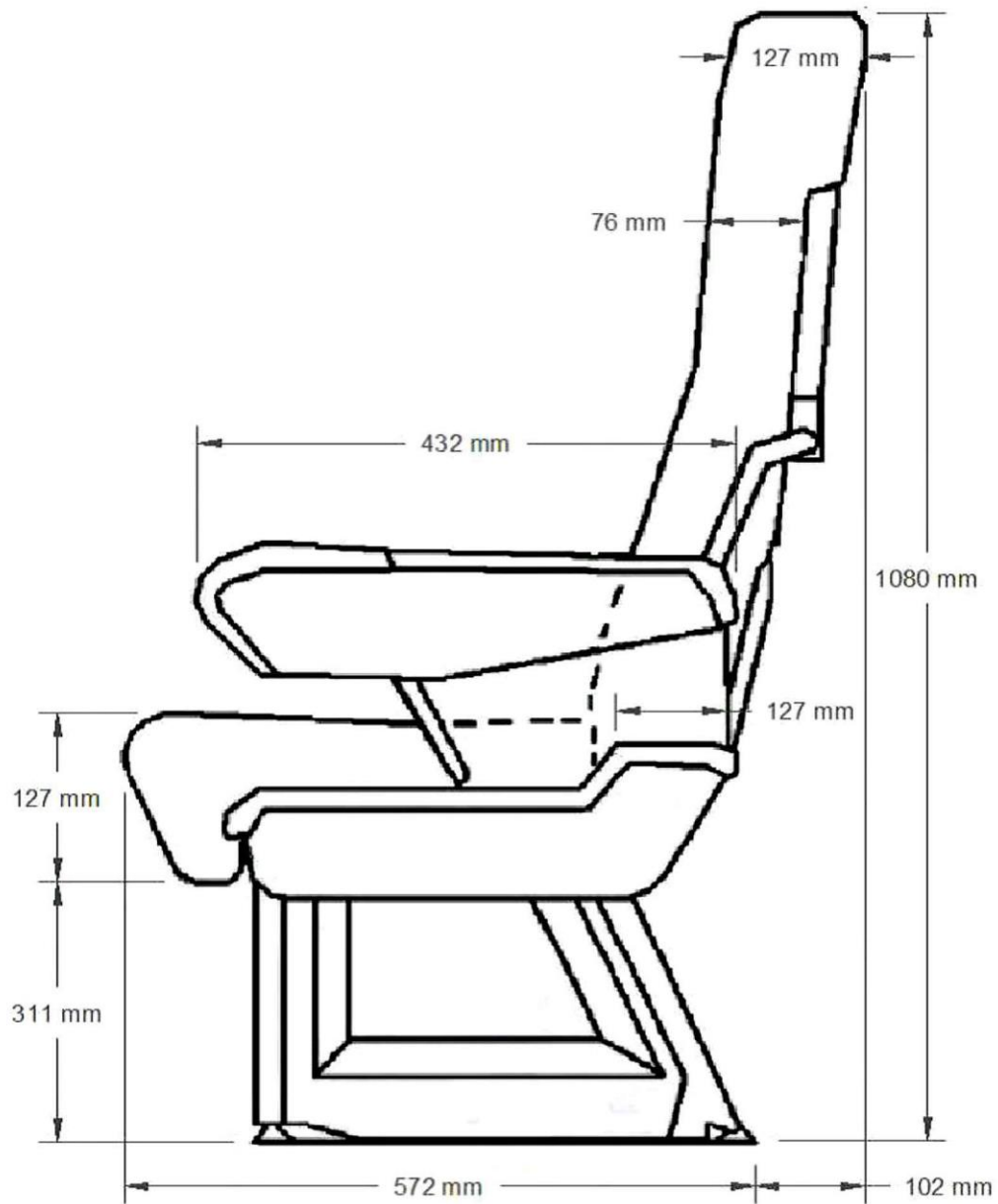


Figure 3.8: Seat Profile Dimensions (Trupka, 2011)

3.1.3: Thermal Manakins

Each seat is occupied by a thermal manakin. The manakins were not heated during the experiments documented here, but were present during all testing. The manakins themselves are Rubie's Costume Company model 1724 inflatable male manakins, specified to 6ft in height.

3.2: Air Supply System

As the ACER laboratory 767 mock cabin is meant to simulate the environment of an aircraft cabin, care must be taken to maintain the ambient cabin conditions at representative values. The air supply system for the mock cabin is designed to supply the cabin with treated air at 1400 cfm and 60° F. Outside air is drawn in and treated by a Munters's ICA-0750-020 desiccant dehumidifier. From the dehumidifier it is then cooled (and/or heated) as necessary by the control loops before being passed into the cabin. The next subsections discuss how each of these control loops is implemented, and the general layout of the air supply system.

3.2.1: Ductwork

Before the supply (ambient) air enters the cabin it must go through the conditioning process and the associated ductwork connecting the processes. Entrance ductwork can be seen in Figure 3.9; exit ductwork can be seen in Figure 3.10.

From the outer wall of the building, air is drawn in through a rectangular duct 0.91 m wide and 0.61 m tall and 2.2 m long into the Munters conditioning unit.

Exiting the Munters unit the ductwork has a 3.8 m section of 0.41 m diameter until reaching a 90° right hand bend. From the bend, the ductwork extended another 1.51 m of 0.41 m diameter until a 90° upwards bend. The upward bend connects a 3.96 m section of duct of 0.41 diameter. The ductwork terminates with a 90° horizontal bend that connects the ductwork to the Boeing supply duct; the supply duct and connections can be seen in Figure 3.11 and Figure 3.12. A simple guillotine valve midway in the 3.96 m upward duct diverts the air to the 767 cabin (option of diverting air to 767/737 cabins). The Boeing supply duct is an original and salvaged 767 supply duct that feeds the linear diffuser through 34 connectable tubes.



Figure 3.9: Entrance Munters Ductwork



Figure 3.10: Exit Munters Ductwork



Figure 3.11: Boeing Supply Duct



Figure 3.12: Connections to Linear Diffuser

3.2.2: Air Conditioning System

Conditioning the air to FAA in-flight standards requires 3 control loops, described in detail here.

The air conditioning system consists of a blower, dehumidifier, hot-water heater, water chiller, and electric heater. The primary loop consists of two heat exchangers, flow meter, and pump. The heat exchangers interface with the cooling and heating loops; the cooling loop contains the water chiller, and the heating loop contains the hot-water heater, respectively, as shown in Figure 3.13 and Figure 3.14.

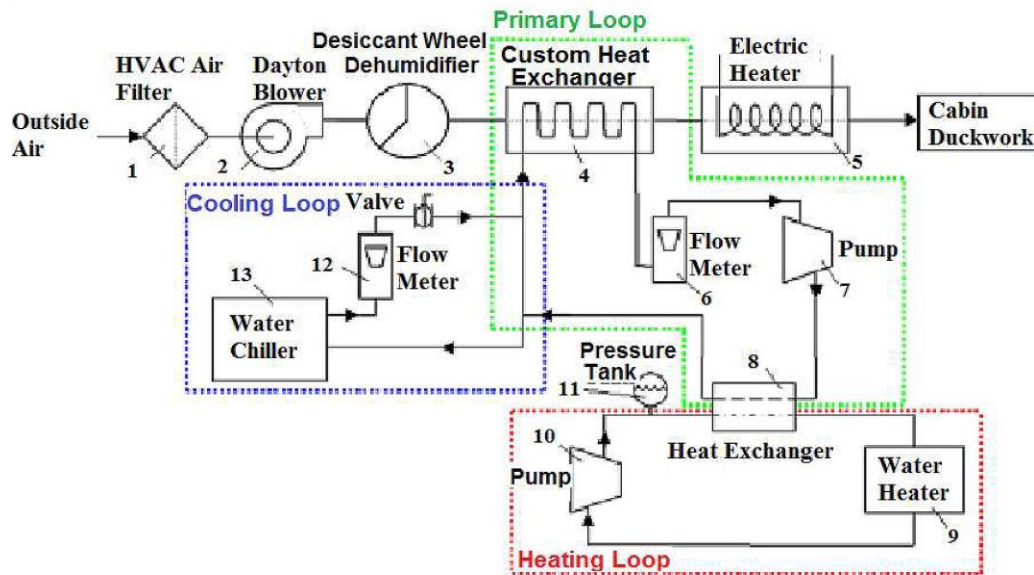


Figure 3.13: Conditioning System Diagram

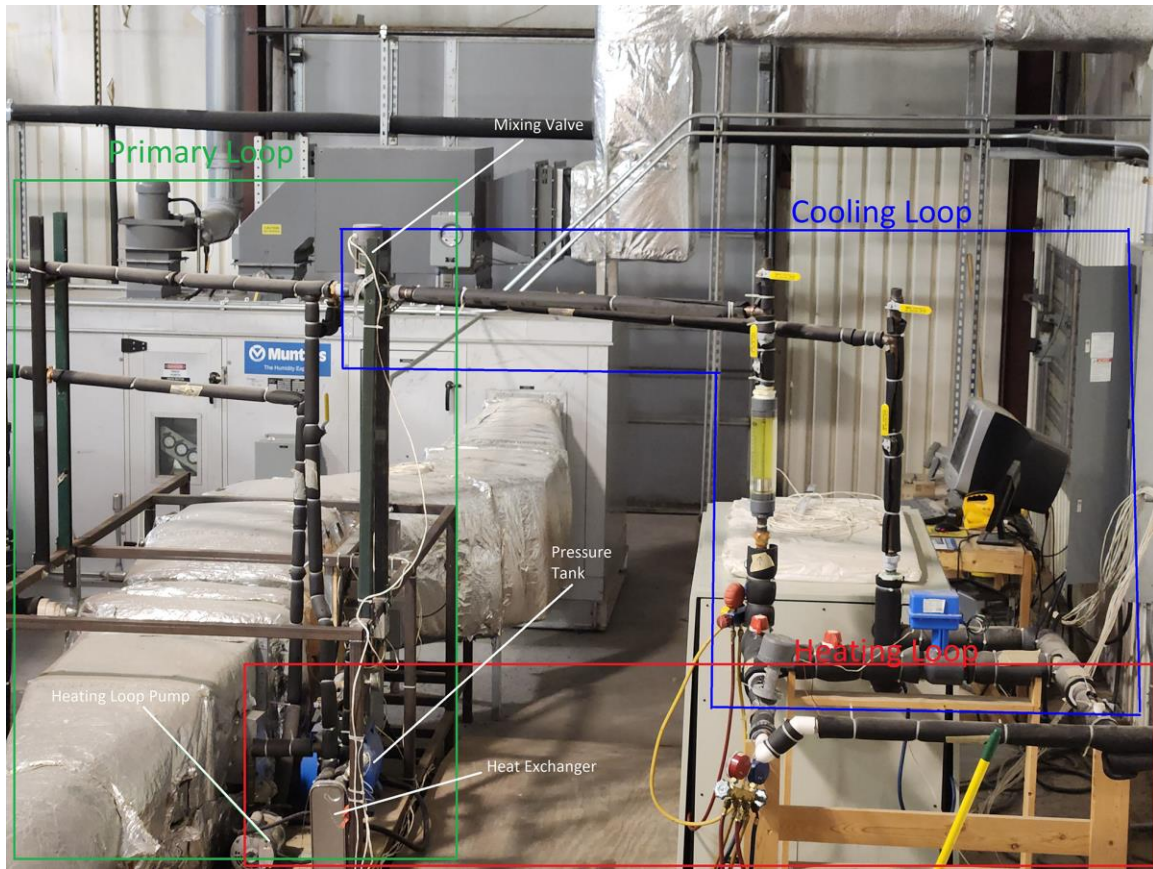


Figure 3.14: Conditioning System

The cooling and heating loops are used to bring the cabin supply (inlet) air to 60° F, depending on the outside conditions. Before entering the primary loop, outside air is treated by a desiccant wheel dehumidifier. Table 3.1 lists the description for each component, reproduced from (Madden, 2015).

Table 3.1: Air Conditioning System Components (Madden, 2015)

No.	Item	Model	Details
1	HVAC Air Filters	Glass Floss ZL	Parallel filters, 24" x 24" x 2"
2	Blower	12025" Dayton Blower, 3.0 hp	Yaskawa GPD315/V7 VFD

3	Dehumidifier	Munters ICA-0750-020	Desiccant type
4	Heat Exchanger	custom	0.6 x 0.6 m
5	Electric heater	AccuTherm DLG-9-3	240 V, 3hp, 9kW
6	Flow meter	Omega FI7204	
7	pump	Marathon CQM 56C34D212OF P	120 V, 0.75 hp
8	Heat Exchanger	Alfa Laval CB27-18H T06	
9	Water heater	Rheem GT-199PV-N-1	19,000–199,900 BTU
10	Pump	FHP C4T34DC35A	Yaskawa GPD205-1001 VFD
11	Pressure Tank	Dayton 4MY57	6.5 gal, 30 psi
12	Flow Meter	King 7205023133W	
13	Water Chiller	AccuChiller LQ2R15	PV-B311 condensing coils

3.2.3: Control Software

National Instruments LabVIEW software is used for the control and data acquisition of the conditioning system; a screenshot of the LabVIEW UI can be seen in Figure 3.15. All system components are controlled through a single program, which acquires data through an Agilent 34970A and NI FP-1000 DAQ. The control program utilizes a PID scheme to control output

signals that are sent through the FP-1000 DAQ with add-on modules PWM-520 and AO-210, used for pulse width modulation and analog voltage output, respectively (Trupka, 2011).

Air temperature, flow rate, and humidity are all controlled by the system. Air temperature is recorded at seven locations in the stream, while percent relative humidity and flow rate are measured downstream of the humidity and temperature processes. Any changes to air temperature are made by the electric heater downstream of the heating/cooling loops; the airflow rate is controlled by varying the blower speed. There is one manually controlled variable: that of the temperature set point of the AccuChiller LQ2R15 chiller. However, the off/on state of the chiller is accounted for by the control software, making the chiller set point not critical.

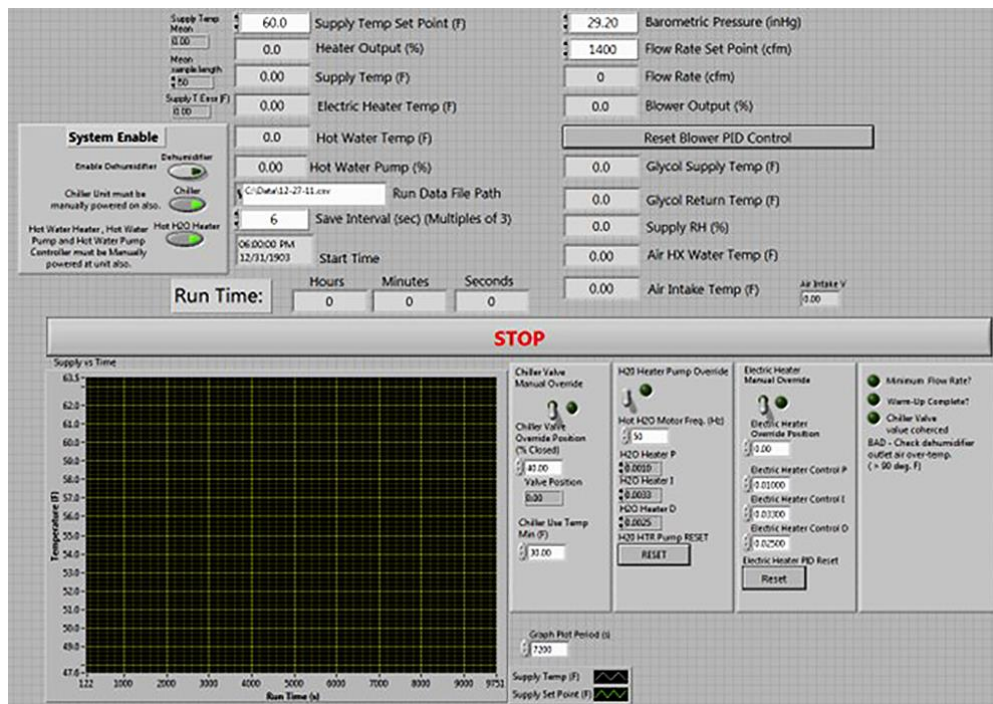


Figure 3.15: Supply Air UI

Details of the feedback and control variables are given in Table 3.2, reproduced from (Madden, 2015).

Table 3.2: supply air conditioning system control (Madden, 2015)

Feedback	Sensor Location	Control
Supply air temp	Cabin inlet duct	Heater temperatures
Electric heater temperature	Thermistor in heater	Heating loop pump VFD
Hot water temperature	Water heater exit	Mixing valves
Supply flow rate	Cabin inlet duct	Blower VFD
Glycol supply temperature	Chiller exit line	Duct heater
Glycol return temperature	Chiller inlet line	Duct heater
Supply relative humidity	Cabin inlet duct	none
Heat exchanger temperature	Primary water loop	None
Air intake temperature	Dehumidifier inlet	none

3.3: Tracer Gas Injecting and Sampling

In an effort to study the effects of virion transport due to respiration, tracer gas was injected and sampled at multiple seat locations in the cabin repeatedly. Carbon dioxide is used as a tracer gas for its stability, low cost, and availability as CO₂ has a density greater than that of air, it is mixed with helium to achieve neutral buoyancy and then injected into the cabin. A negative buoyancy for injected tracer gas is undesirable, as it is possible that the injected plume will sink, disrupting dispersion and affecting subsequent data collection.

3.3.1: Tracer Gas Injection

The tracer gases used are manufactured by Matheson Tri-Gas; specifically CO₂ and high purity helium in 50 lb cylinders, both stored close to their respective mass flow controller. As the gases are highly pressurized, regulators keep the supply pressure at a safe and stable level (200

kPa/29 psi) for the vinyl tubing connections before entering the mass-flow controllers, as shown in Figure 3.16. As stated above, each gas has its own mass-flow controller that enables separately controlled flow rates to be used, ensuring the proper mix of gases prior to injection.



Figure 3.16: Gas Tanks with Regulators

Downstream of the gas cylinders, mass flow controllers regulate the precise control of the injection rate. For CO₂, a MKS 1559A-200L-SV-S (100 SLM model) is used, and for helium a MKS pneumatic 2179A00114CS1BV model, as seen in Figure 3.17. The pneumatic model requires ~85 psi of air to operate the piston correctly. Both mass-flow controllers are powered and signaled by a MKS PR4000 power unit paired with an RS-232 interface unit for interfacing with LabVIEW software for control (Figure 3.26).



Figure 3.17: MKS Mass Flow Controllers

Secondary flow rate measurements are enabled by visual-type Omega flow meters downstream of the digital MKS mass-flow controllers, seen in Figure 3.18.

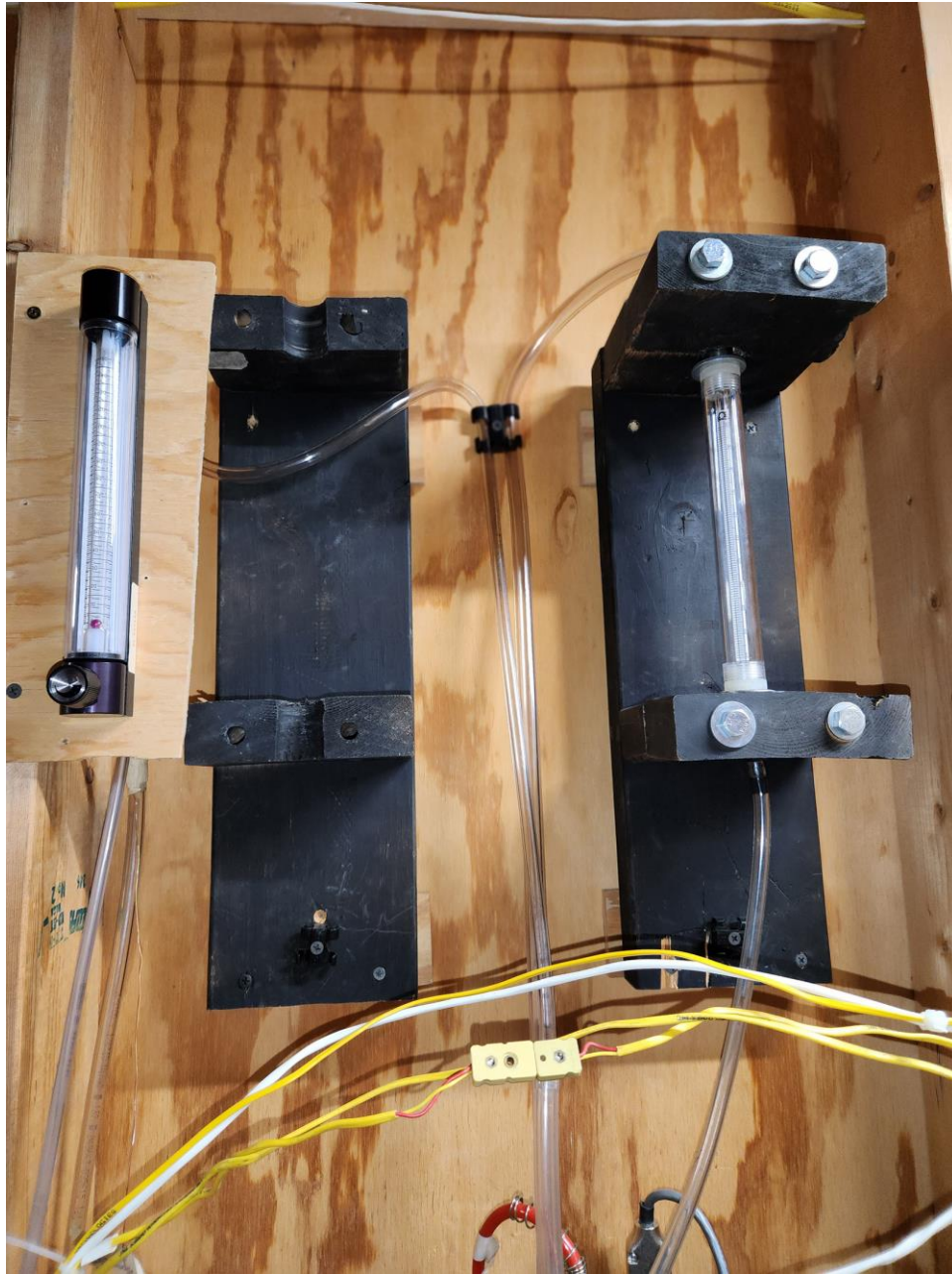


Figure 3.18: Omega Visual Flow Meters

Downstream of the mass-flow controllers, prior to injection, the gases are mixed in a brass T fitting. At the injection point, the gases are expelled through a vertically mounted tube with its opening 1.2 meters from the cabin floor; the apparatus holding the tube vertical sits on

the source seat. All tests conducted maintained 8 SLM of gas injected: 5 SLM of CO₂ and 3 SLM of He, which produces an exit velocity from the copper tube of 0.2631 m/s, and ensures proper buoyancy of the mixture. A complete mass-balance on the gas species used and logic behind their flow rates can be found in (Mahmoud, 2021).

3.3.2: Tracer Gas Sampling

Carbon dioxide concentrations (in ppm) at 6 locations in the cabin are recorded during the entire duration of each experiment run. The sampling locations are discussed further in chapter 4, as they are more pertinent to the experimental procedure. The concentrations in question are measured directly by 6 non-dispersive infrared CO₂ analyzers, each responsible for an individual location. The number and models of the analyzers used are: 3 PP Systems WMA-4, 2 PP Systems WMA-5, and 1 custom Edinburgh Gaspard NG, of which can be seen in Figure 3.20, Figure 3.21, and Figure 3.22. The custom analyzer utilizes an Edinburgh Instrument gas sampling card, on 24 V power and a 60 Hz noise filter (Trupka, 2011). The WMA-4 and Edinburgh analyzers require the use of a single, separate, air pump (seen in Figure 3.19) to pull the sampled air from the cabin through the vinyl connecting tubes and into the analyzers. The pump is connected downstream of the analyzers. The WMA-5 models have a built-in pump, negating the need for an external one. Table 3.3 lists the specific details of each model.

Table 3.3: CO₂ Analyzer Details

Sensor Model	CO ₂ Concentration Range	Output Voltage Range
Edinburgh Gascard NG	0-2000 ppm	0-5 V
PP Systems WMA-4	0-2000 ppm	0-5 V
PP Systems WMA-5	0-3000 ppm	0-2.5 V



Figure 3.19: Analyzer External Pump



Figure 3.20: WMA4 Analyzers



Figure 3.21: WMA5 Analyzers

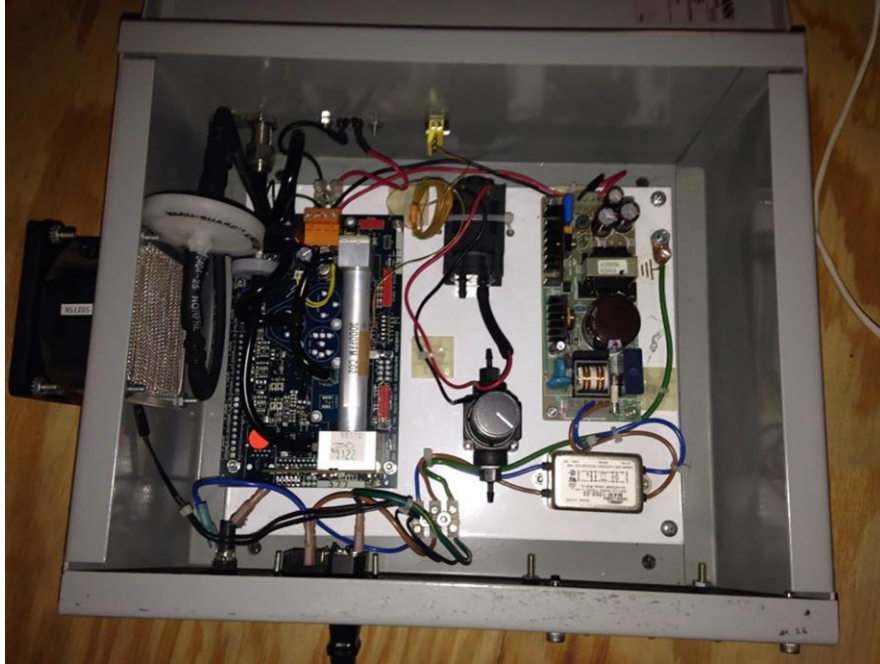


Figure 3.22: Edinburgh Analyzer

A balancing system upstream of the vacuum pump ensures each of connected analyzers drawn in 1 SLM of sampled air from the cabin. The system is comprised of an Omega FL-2012 flow meter, which has 3 needle valves for adjustment of individual flows. As there are 4 analyzers connected, one flow chamber is connected to 2 sensors, and the flow rate through it doubled to 2 SLM, as shown in Figure 3.23.



Figure 3.23: Flow Balancing System

In previous studies at ACER (see Mahmoud, 2021; Shehadi, 2015; Madden, 2015, Darrah, 2018), analyzers were used to sample locations differently; in particular, a single analyzer was connected to a custom sampling tree. The sampling tree enabled steady state measurements at single locations on the tree, each 0.84 meters apart (distance from center of one seat in a row to the center the seat directly in front/behind it). As the tree does not allow for simultaneous measurements at all locations on the tree, it was not directly used in these experiments. However, the spacing of its sampling tubes provided solid attachment points for the individual vinyl sampling tubes at the correct distances, which are in turn connected to individual CO₂ analyzers; thus the sampling tree ensures precise sampling points at the seats emanating from the injection source. The sampling tree with the attached vinyl sampling tubes is shown in Figure 3.24, while the injection source apparatus is shown in Figure 3.25.



Figure 3.24: Sampling Tree Base



Figure 3.25: Tracer Gas Injection Source

3.3.3: Control Software

The entirety of the gas injection system, as well as the data acquisition unit, is controlled remotely by LabVIEW software. The sampling rate and mass-flow set points of the tracer gas species are fully adjustable: as stated previously, 5 SLM of CO₂ and 3 SLM of He were injected,

while the sampling rate is set to record measurements every 5 seconds. Testing periods are set by the number of scans (samples) in each period. In previous experiments where the sampling tree was used, “Test scans per location (GAS On)” was utilized, as it also enabled the selection of individual ports on the sampling tree. As this present study looks at simultaneous measurements (without interfacing or with the sampling tree), this interval section is set to 0 scans, while the “S.S. delay scans (GAS ON)” period was set to the proper number of scans for the injection type (see Ch. 4). The number of scans per period multiplied by the scan interval gives the total time of data acquisition for each period (and the time of gas injection, where applicable).

Data is output to multiple comma-separated values files (.csv) that are easily converted to Excel (.xlsx) files for analysis. The data is collected by an Agilent 34970A DAQ, collecting from all six CO₂ analyzers, and 24 thermistors, 12 per cabin wall. The power supply, and DAQ, and LabVIEW frontend UI are shown in Figure 3.26 and Figure 3.27, below.



Figure 3.26: PSU and DAQ

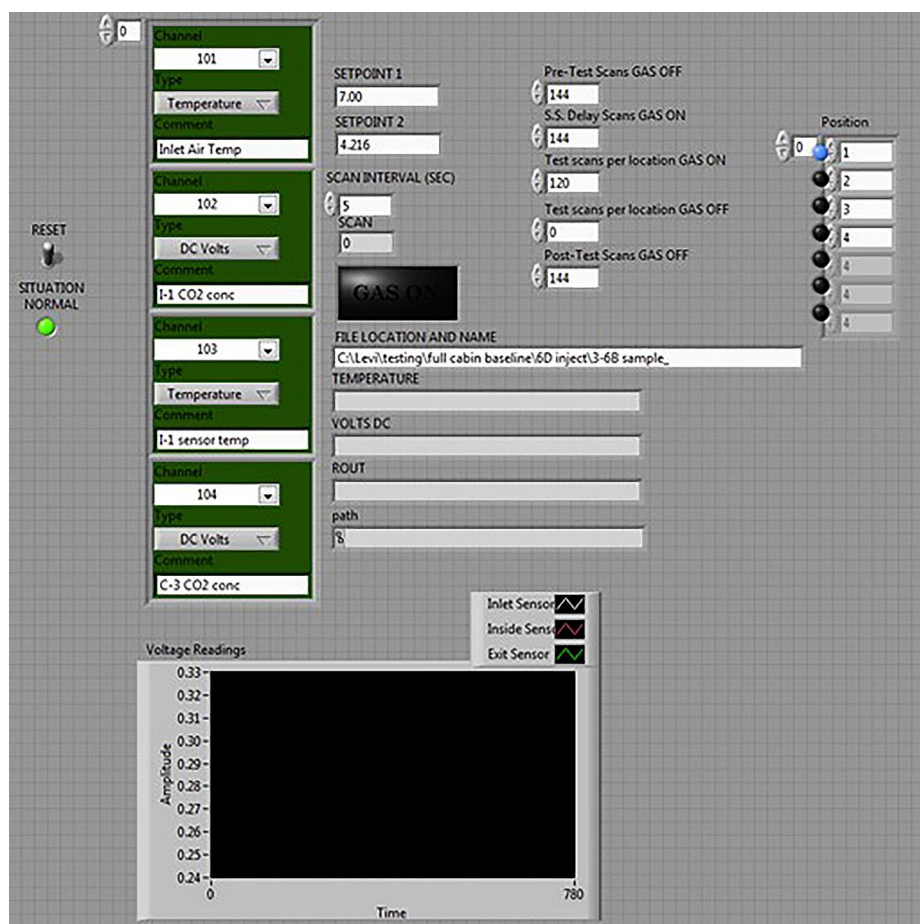


Figure 3.27: Tracer Gas Injection Software UI

Chapter 4 - Experimental Procedure

All testing procedures utilized for the experiments of this thesis are described here. The most important aspects to note are the location of the injection source, and the type of injection being conducted.

4.1: Injection Source Cabin Location

The injection source (see Figure 3.25) location for the tracer gas used in these experiments was varied at two different locations in the 767 cabin mockup; that is all tests were conducted with the injection source at either Row 7 Seat D (the middle of the entire row) or Row 7 Seat G (the right side window seat of the same row). For each testing location over the duration of each test, five analyzers measure the instantaneous CO₂ concentration (in ppm) at positions emanating from the source, and one analyzer measures the incoming ambient supply air carbon dioxide concentration (in ppm). The tested source locations and locations of analyzer inlets (the vinyl tubing that leads to the analyzers in the hallway) can be seen in Figure 4.1 and Figure 4.2. In these figures, the source is denoted by the red circle, and the positions of the sensors are denoted by their corresponding number in blue. The numbering of the sensors begins at 1 nearest the source and terminates at 4 furthest from the source. Position 1 is 0.84 m from the source, and position 2 is 0.84 m away from position 1 (or 1.68 m from the source – see Figure 3.24) Positions 3 and 4 follow the same distance scheme. The position behind the source, which is the same distance from the source as sensor 1 but in the opposite direction in the cabin, is denoted by position (-1). The 6th analyzer which measures ambient supply air carbon dioxide concentration is attached inside the linear diffuser where it is not affected by the gas being injected within the cabin.

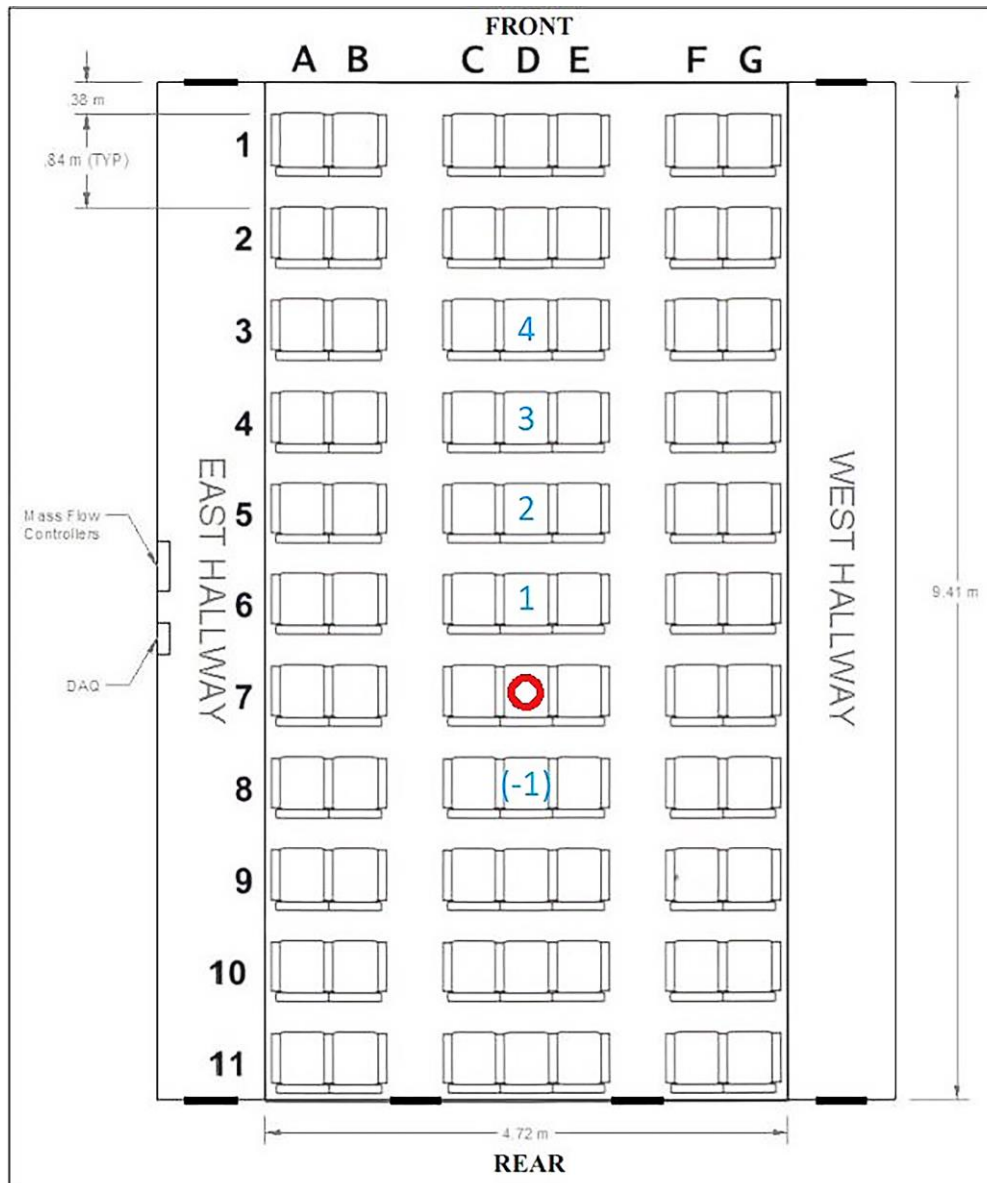


Figure 4.1: Row 7 Seat D Setup (r7sD)

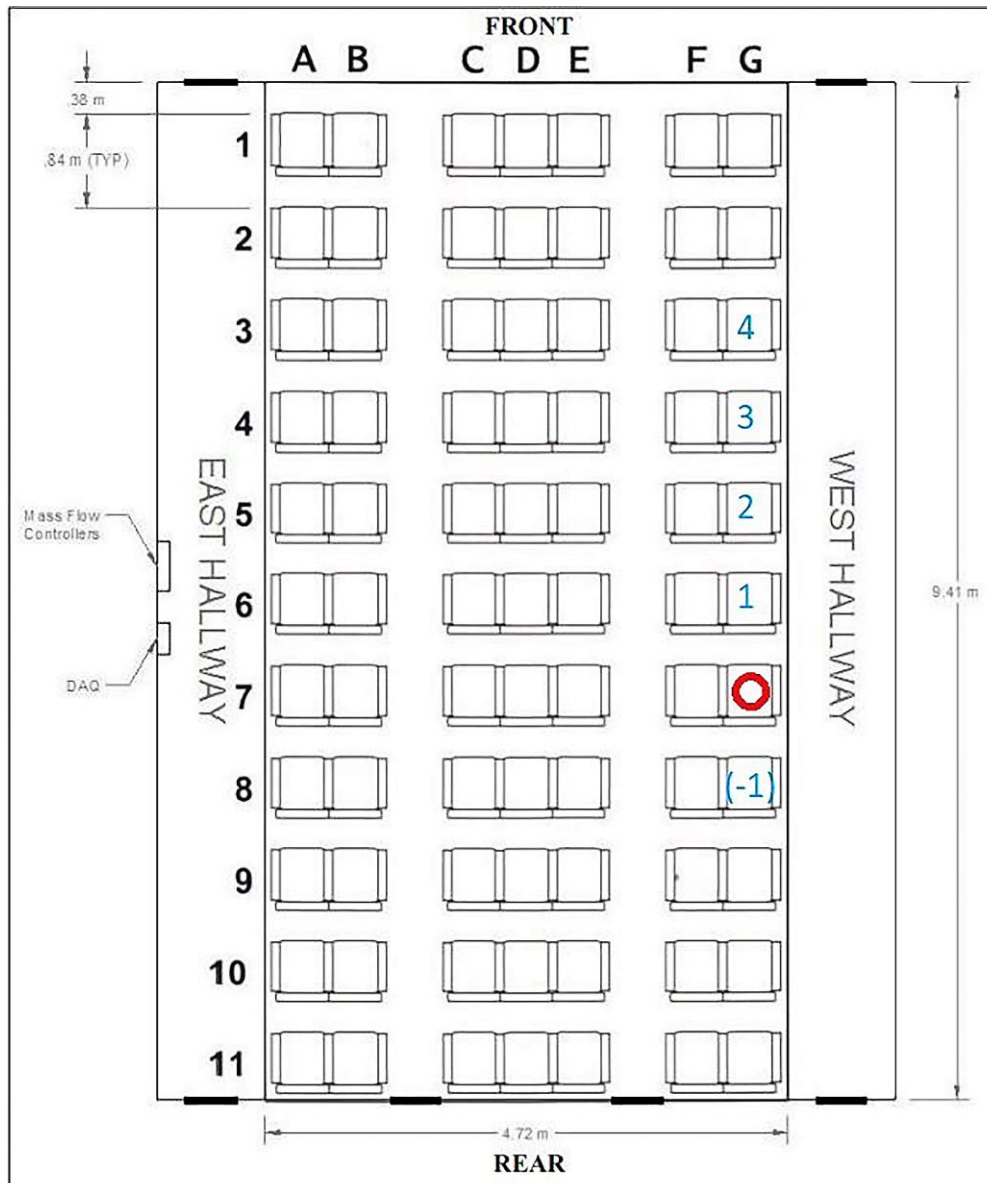


Figure 4.2: Row 7 Seat G Setup (r7sG)

4.2: Injection Durations

The carbon dioxide injection durations were varied to simulate different respiration conditions and for comparison of test results to previous work. Four different injection duration techniques were used in this current study, and they are summarized in Table 4.1.

4.2.1: One-Minute Puff Type

The 1-minute puff type injection is the shortest duration of gas injection that was tested. Each test of the 1-minute puff type injection has a 30-minute steady state (pre-gas) period with no tracer gas injection. This pre-gas period is intended to establish baseline values for the analyzers. Then there is a one-minute tracer gas injection period. Immediately following this one-minute injection, there is a 45-minute post-gas period with no tracer gas injection during which the response to the puff injection is measured. Once the concentration(s) return to steady state, near the end of the 45-minute post gas period new baselines are established for the sensors. The baseline values are for analysis purposes, and will be referenced extensively in chapter 5.

4.2.2: Three-Minute Puff Type

The 3-minutes puff type injection is simply an extension of the 1-minutes puff injection type. The 3-minutes puff has a 30-minute steady state (pre-gas) period with no tracer gas injection (to establish analyzer baseline values). This is immediately followed by a 3-minutes tracer gas injection period. Immediately following the injection period there is a 45 minutes (post-gas) period with no tracer gas injection. This period serves the same purpose as the 45 minutes post-gas period as the 1-minute puff; to record the response to the injection and later to establish post-gas baseline values.

4.2.3: Continuous Type

The continuous type injection begins with a 30-minute steady state (pre-gas) period with no tracer gas injection to establish analyzer baseline values. This is followed by a 45-minute continuous (constant) tracer gas injection period, and finally followed by a 45-minute (post-gas) steady state period with no tracer gas injection. Again, this is to record the diffusion of the injection response and later to establish post-gas baseline values.

4.2.4: Long Continuous Type

The long continuous type injection begins with a 30-minute steady state (pre-gas) period with no tracer gas injection (to establish baselines). Following this period there is a 3.5 hour (210-minute) continuous (constant) tracer gas injection period. After the injection period, there is a 45-minute (post-gas) steady state period with no tracer gas injection. The 45-minute post-gas period serves the same purpose as the regular continuous type. This injection type represents the longest injection type tested, and is over 4 times longer than the regular continuous injection type. This method was used to observe any large changes in CO₂ dispersion rates that are more difficult to capture over shorter time periods.

Table 4.1: Summary of Injection Types

Injection Type	Pre-gas S.S. period	Injection period	Post-gas S.S. period
1-min puff	30 min	1 min	45 min
3-min puff	30 min	3 min	45 min
Continuous	30 min	45 min	45 min
Long continuous	30 min	210 min	45 min

4.3: 5-Way T

For the long continuous type injections tests, of which 4 were conducted with 2 at each injection source location (see section 4.1), 1 test at each location was conducted with a 5-way T attached to the source injection port (Figure 4.3).



Figure 4.3: 5-Way T

This was done in an effort to uniformly distribute the tracer gas in the 4 cardinal directions evenly before it was influenced by the local air currents in the cabin.

4.4: Thermal Manakins

As stated previously (see ch 3.1.1), manakins occupy all seats in the cabin save the one seat reserved for the injection apparatus. The manakins were not heated for any tests in this current study to limit the number of variables affecting air flow (local air currents) and subsequent CO₂ dispersion. Thus while the manakins' presence does account for effects of airflow disruption due to occupied space, it does not allow for analyzing the effects of heat load. For effects of heat load from thermal manakins, see (Mahmoud, 2021).

4.5: Gaspers

The gaspers (individual seat air nozzle) for each row were not utilized in any tests run in this current study. This was again to limit the number of variables affecting local air currents in the cabin. For effects of gaspers on airflow distribution and CO₂ concentrations, see (Mahmoud, 2021).

4.6: Analyzer Warm-Up

While not highlighted in the general descriptions of the injection types, before any tests were conducted for a given day, the analyzers required a warm-up period of one hour separate prior to the steady state period at the beginning of each test. The recommended time specified by the manufacturer is 30-minutes; one hour was used to ensure stability in the analyzers, as they do zero themselves during testing, and improper warm-up can result in overcompensation during these zeroing events, which affects baseline value calculations (see details in Chapter 5 -).

Chapter 5 - Data Reduction Techniques

Proper analysis of the experimental data requires careful data reduction and presentation of test results in the most useful form in answering a relevant engineering and scientific question. In this present study, the most useful quantity is the *percent relative exposure*. Reduction of data obtained from each analyzer to this value requires separate numerical techniques for the puff and continuous injection types, as they are separate methodologies.

5.1: Percent Relative Exposure

Previous studies at ACER (Mahmoud, 2021; Darrah, 2018; Patel, 2017; Shehadi, 2015) focused on the continuous injection type. The impetus for this present study was experimental validation of ACER's data to that of the TRANSCOM study, which are based on a puff injection. The question must then be asked whether puff vs continuous injection types produce different results.

At a given location, the TRANSCOM data is expressed as a fraction of the injected contaminant inhaled; that is the amount detected (inhaled) at each location vs the total contaminant injected into the cabin. As such, for comparison, the data for this present study was reduced so as to be expressed in the same manner. However as we use tracer gas, the contaminant is carbon dioxide. The fraction (before conversion to a percentage) is given as:

$\frac{\text{detected (inhaled) } CO_2}{\text{total injected } CO_2}$. This is the detected carbon dioxide at a given location over the total injected carbon dioxide.

5.2: Puff Type

The puff type injection tests require integration of the carbon dioxide (ppm) values over time during the puff until theoretically the recorded ppm at all positions have returned to their

pre-puff baseline values. However, in practice, the recorded ppm values never return to their original baseline values due to the change in concentration within the cabin. This leads to challenges in the integration itself: too long of an integration period leads to an over-estimation of the relative exposure value, and too short an integration leads to an under-estimation. Examining the multiple preliminary tests led to the decision of using a 15-minute integration period, which allows for sufficient time for ppm values to return to baselines without over-estimating the relative exposure. The equation used to reduce the data for both 1-minute and 3-minute puff types is given as:

$$F_i = \left(\int (C_i(t) - C_{i,base}) \dot{V}_{res} dt \right) \cdot \frac{1}{\dot{V}_{in} \Delta t_i} \quad (1)$$

The terms and their descriptions for Equation (1) are listed below in Table 5.1.

Table 5.1: Puff Integration Equation Terms

Equation Term	Use
$C_i(t)$	Concentration in ppm of position (sensor) i at time t
$C_{i,base}$	Baseline concentration in ppm of position (sensor) i
$\dot{V}_{res}$	Respiration volume flow rate [7.5 SLM]
$\dot{V}_{in}$	Carbon dioxide volume injection flow rate [5.0 SLM]
Δt_i	Length of time of puff injection [1-min or 3-min]
Δt_s (see 3.3.3: Control Software)	Time in between measurements [$\frac{1}{12}$ min]
F_i	Percent relative exposure

The integration is done with respect to time, dt. Numerically, the integration is accomplished using a summation over the 15-minute integration period:

$$F_i = \left\{ \sum (C_i(t) - C_{i,base}) \right\} \cdot \frac{\dot{V}_{res} \Delta t_s}{\dot{V}_{in} \Delta t_i} \quad (2)$$

The summation term (which is in parts per million) when fully summed is then divided by 10^6 to put into fraction (decimal) form. Finally, multiplication by 100% gives the relative exposure as a true percentage. To be clear, as an example, the summation term for a single evaluation would be 498 – 440, as the voltages are converted to ppm values, not the decimal. This is why division by 10^6 is necessary.

As was stated in the experimental procedure of Chapter 4 - , there are 3 distinct phases of each experiment (see Figure 5.1), the pre-gas period, the injection (gas-on) period, and post-gas period. During the 30-minute pre-gas phase, a baseline is calculated during the final 10 minutes before injection for each sensor (location). The baseline is taken as an average ppm value of that sensor over the 10 -period in question. The injection period follows this, and then the post-gas period, where another baseline is calculated from the 30th to 40th minutes (out of the 45-minutes post-gas phase), again for each sensor (location). These two baselines, the pre-gas and post-gas baselines, are then averaged yielding the nominal baseline which is used in the reduction calculations. Thus, each sensor has a nominal baseline value that represents its steady state condition; that is no tracer gas being injected, cabin ambient supply air on only.

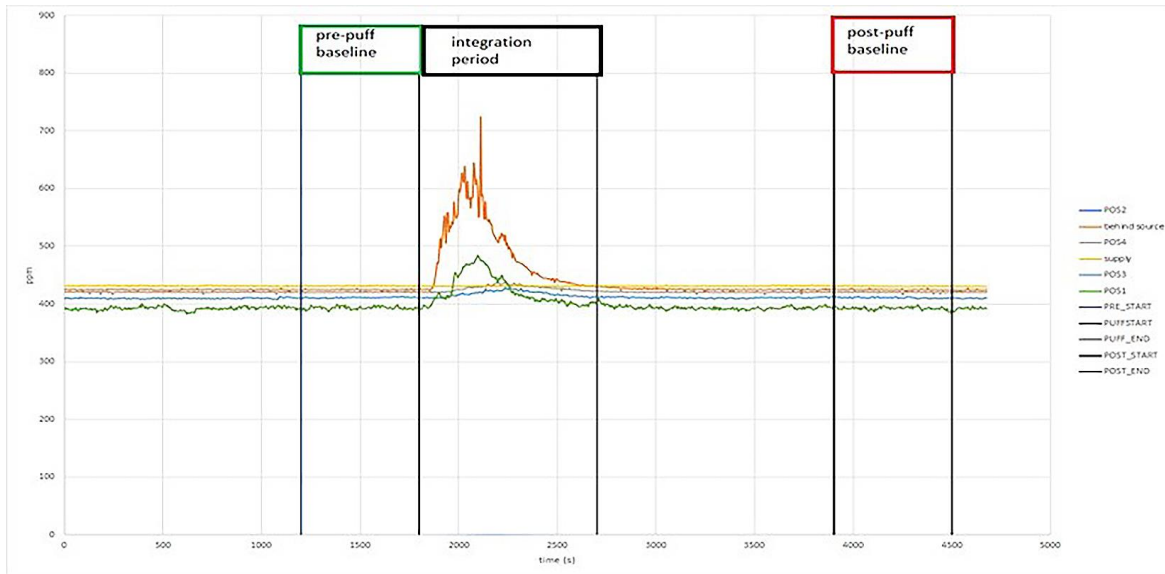


Figure 5.1: Puff Test Phases

5.2.1: Puff Ambient Air Offset

An issue that became apparent is that over the course of a day, ambient air CO₂ concentrations may vary. The ACER Laboratory is situated in a mixed industrial/commercial zone. This present study takes into account the possibility that over the course of a complete test, the carbon dioxide concentration in the ambient incoming cabin air could rise or fall based on the outdoor environmental conditions where the air is pulled from before conditioning. Preliminary tests showed that for most tests, the difference between the pre and post-gas baselines was small. However, large changes in the ambient have direct effect on the CO₂ (ppm) concentrations recorded for each sensor (location). If the ambient rises significantly, a subsequent rise can be seen in all position sensors, and this adversely affects the overall data reduction. As such, a measure was taken in the data reduction to account for the carbon dioxide concentrations in the ambient air, even minute ones. For the puff tests, the offset was incorporated into the summation term, where the average baselines are swapped for only pre-puff baselines (in an ideal world they would be the same). In doing so the formula accounts for changes (drifts) in the ambient over the

duration of the test, and also for changes (drifts) in the sensors themselves during the test. The formula takes the ambient air pre-puff baselines and subtracts it from the instantaneous ambient concentration; this term is then subtracted from pre-puff baseline of position **i**, and finally this resultant term is subtracted from the instantaneous concentration at position **i**. A generalization of the formula is given by:

$$\int (C_i(t) - C_{i,base}) dt = \int \{C_i(t) - [C_{i,pre-puff} + (C_{ambient}(t) - C_{ambient,pre-puff})]\} dt \quad (3)$$

The terms and their descriptions are detailed below in Table 5.2.

Table 5.2: Puff Ambient Offset Terms and Descriptions

Term	Description
$C_i(t)$	Concentration in ppm of position (sensor) i at time t
$C_{i,base}$	Baseline concentration in ppm of position (sensor) i
$C_{i,pre-puff}$	The pre-gas average concentration in ppm for position i
$C_{ambient}(t)$	The instantaneous concentration of the ambient supply air (cabin inlet) at time t
$C_{ambient,pre-puff}$	The pre-gas average concentration for the ambient supply air (cabin inlet)

The integral is evaluated the same as before, as a summation, over the range of time (15 minutes).

$$\sum \{C_i(t) - [C_{i,pre-puff} + (C_{ambient}(t) - C_{ambient,pre-puff})]\} \quad (4)$$

5.3: Continuous Type

For the continuous type test, which is in theory a steady state system save for the brief time periods where the injection starts and ends operation (see Figure 5.2), the general (but not final) calculation is straightforward:

$$F_i = \frac{((C_{i,avg} - C_{i,base})\dot{V}_{res})}{\dot{V}_{in}} \quad (5)$$

The terms and their descriptions are given here in Table 5.3.

Table 5.3: Continuous Reduction Terms

Term	Description
$C_{i,avg}$	Average ppm value for the final 10 minutes of the 45-minute gas-on period of position (sensor) i
$C_{i,base}$	Baseline concentration in ppm of position (sensor) i . Calculated from the average of pre and post gas baselines for position i
$\dot{V}_{res}$	Respiration volume flow rate [7.5 SLM]
$\dot{V}_{in}$	CO ₂ volume injection rate [5.0 SLM]

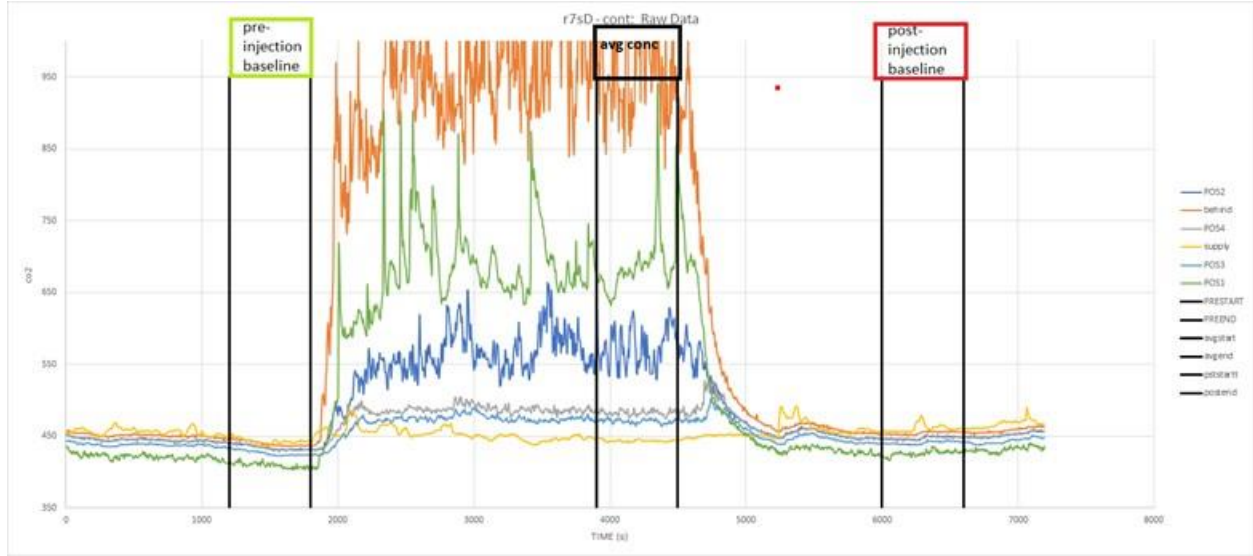


Figure 5.2: Continuous Tests Phases

As the continuous type test is considered a steady state system during the gas-on period, an average, $C_{i,avg}$, is taken as a representative concentration value at each position. The average is taken over the last 10 minutes of the gas-on period to ensure that the value is as close to a steady state representation as possible. The baseline for each position, $C_{i,base}$, is calculated as an average of pre and post gas (injection) period baselines, as was done in the puff type tests.

5.3.1: Continuous Ambient Air Offset

The need for an offset is made more apparent in Figure 5.2, where the fluctuations in carbon dioxide concentrations of the supply air can be seen in directly in the other cabin position concentration measurements over time. As was done for the puff type tests, an ambient supply (cabin inlet) air offset is implemented into the reductions. The offset is accomplished by a summation much like that of the puff type, followed by a division by the number of terms in the summation to bring the value back to an average difference, or the term calculated originally in the un-offset equation: $(C_{i,avg} - C_{i,base})$. The average difference with the offset is generalized by Equation 6:

$$(C_{i,avg} - C_{i,base}) = \frac{\sum\{C_i(t) - [C_{ambient}(t) + C_{i,pre-puff} - C_{ambient,pre-puff}]\}}{n} \quad (6)$$

The terms and their descriptions are listed below in Table 5.4:

Table 5.4: Continuous Offset Terms and Descriptions

Term	Description
$C_i(t)$	Concentration in ppm of position (sensor) i at time t
$C_{ambient}(t)$	The concentration of the supply air (cabin inlet) in ppm at time t
$C_{i,pre-puff}$	Baseline concentration in ppm of position (sensor) i . Calculated from the pre puff baseline for position i
$C_{ambient,pre-puff}$	Pre-puff baseline concentration of the supply air (cabin inlet) in ppm
n	Number of terms in the 10-minute summation

What should be made apparent is that if there is *absolutely no* change in the ambient (supply) carbon dioxide concentration over the time range, then for each summation the $C_{ambient}(t)$ and $C_{ambient,pre-puff}$ will cancel out. When all terms are summed and the sum divided by n, what is left is an average difference, $C_i(t) - C_{i,base}$.

All percent relative exposure reductions are presented in the ambient offset modulated form in this thesis.

Chapter 6 - Overview of Results

This chapter presents an overview of the results for the Row 7 Seat D and Row 7 Seat G testing locations. Specific results are highlighted for the purpose of elucidating the overall trends of the tests, not the bulk analysis, which is presented in Chapter 7.

6.1: Summary of Tests

A total of 123 injection tests are documented herein from study, conducted over the course of a year. Table 6.1 below lists the number of tests per injection type, for Row 7 Seat D, and similarly Table 6.2 lists the number of test per injection type for Row 7 Seat G.

Table 6.1: Tests for Row 7 Seat D

Injection type	Number of tests
1-minute puff	21
3-minutes puff	19
Continuous	13
Long continuous	4

Table 6.2: Tests for Row 7 Seat G

Injection type	Number of tests
1-minute puff	21
3-minutes puff	22
Continuous	19
Long continuous	4

6.2: Typical Responses

It is important in this present study to understand that each injection type has a “typical” response. Through visual inspection of the entire data set (the response graphs) of each injection type, per testing location, a few representative graphs are selected that best encapsulate the general behavior of the corresponding data set. This is done to qualitatively exhibit to the reader what a general response for each injection type looks like. What requires the most attention are the scales for the vertical (ppm) and horizontal (seconds) axis of the response graphs, which differ between injection types in order to capture and show their behavior clearly, and to depict the nature of the responses themselves. (Please note that labels present in the lower right corner are internal designations only. After heavy use the tracer gas tanks run out during tests meaning those tests cannot be used).

6.2.1: Row 7 Seat D

As a reminder, Row 7 Seat D represents the middle of the entire row 7, or the middle seat of the middle triple seat group in a 767 cabin. It is directly under the linear diffusers, and is not near any cabin wall and thus subject to any potential wall effects.

6.2.1.1: Continuous Injection

The continuous injection type tests at Row 7 Seat D show an important characteristic that is a recurring property among all injection test types, that of high variability from result to result. While all continuous injection tests exhibit a degree of chaotic nature in their response graphs, as shown in Figure 6.1 and Figure 6.2, some exhibit significant shifts during the tests, not attributed to ambient supply carbon dioxide concentration fluctuations, as seen in Figure 6.3 and Figure 6.4.

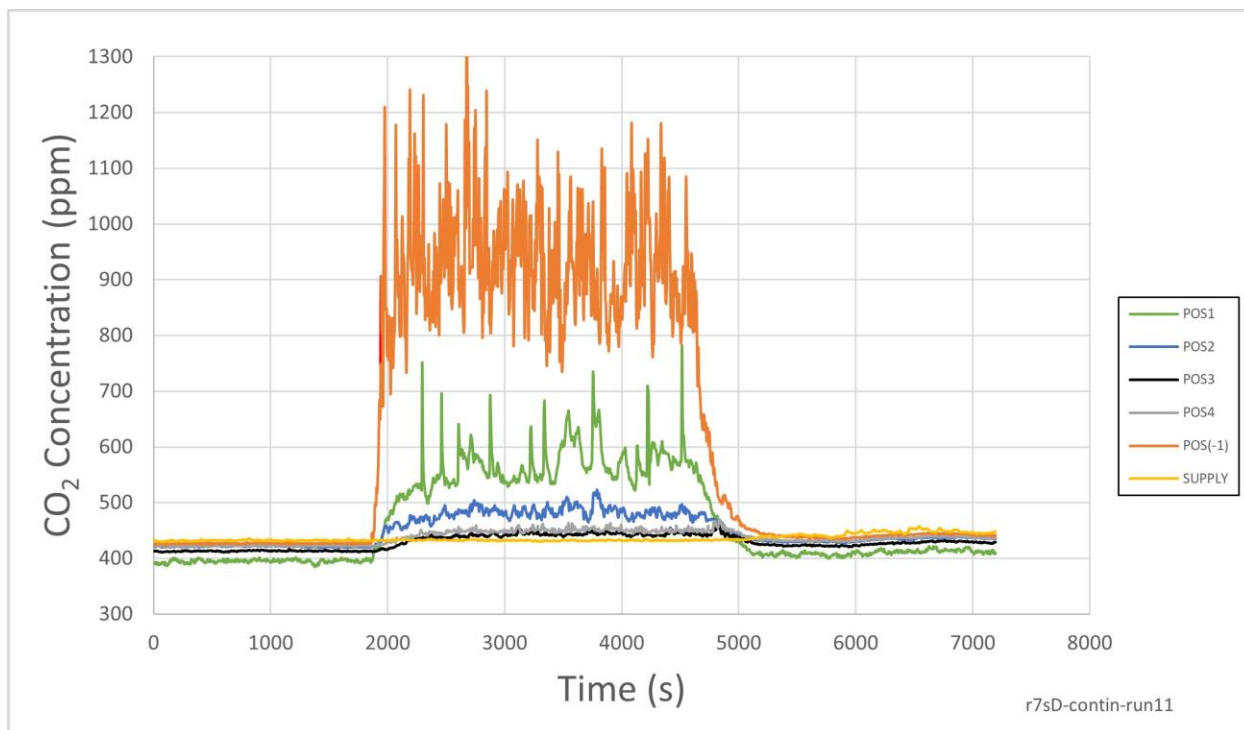


Figure 6.1: Row 7 Seat D Continuous Injection, Run 10

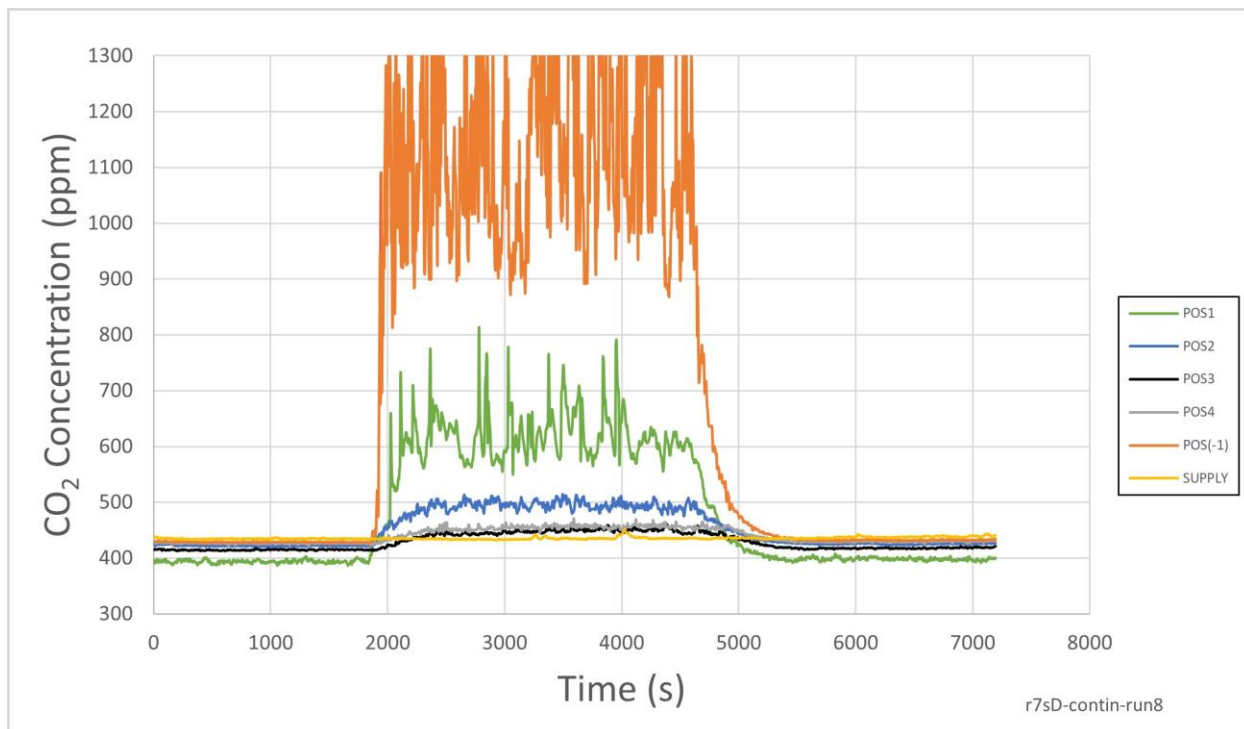


Figure 6.2: Row 7 Seat D Continuous Injection, Run 7

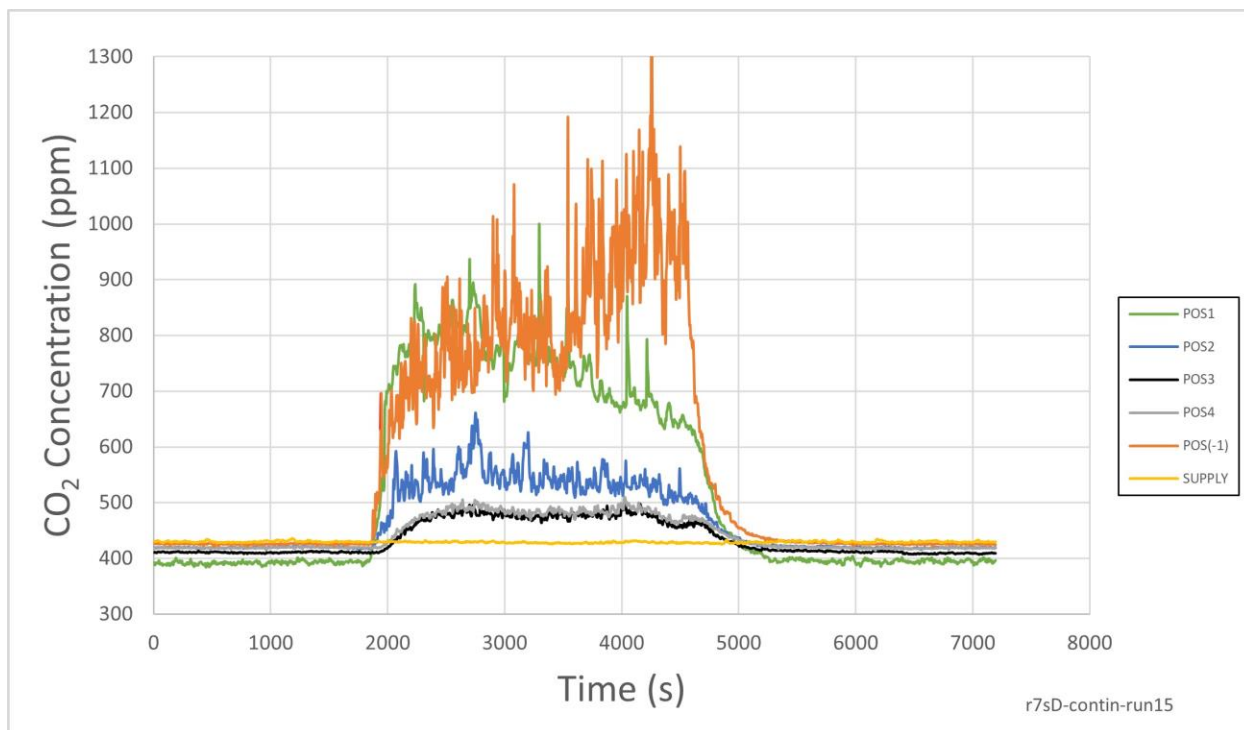


Figure 6.3: Row 7 Seat D Continuous Injection, Run 13

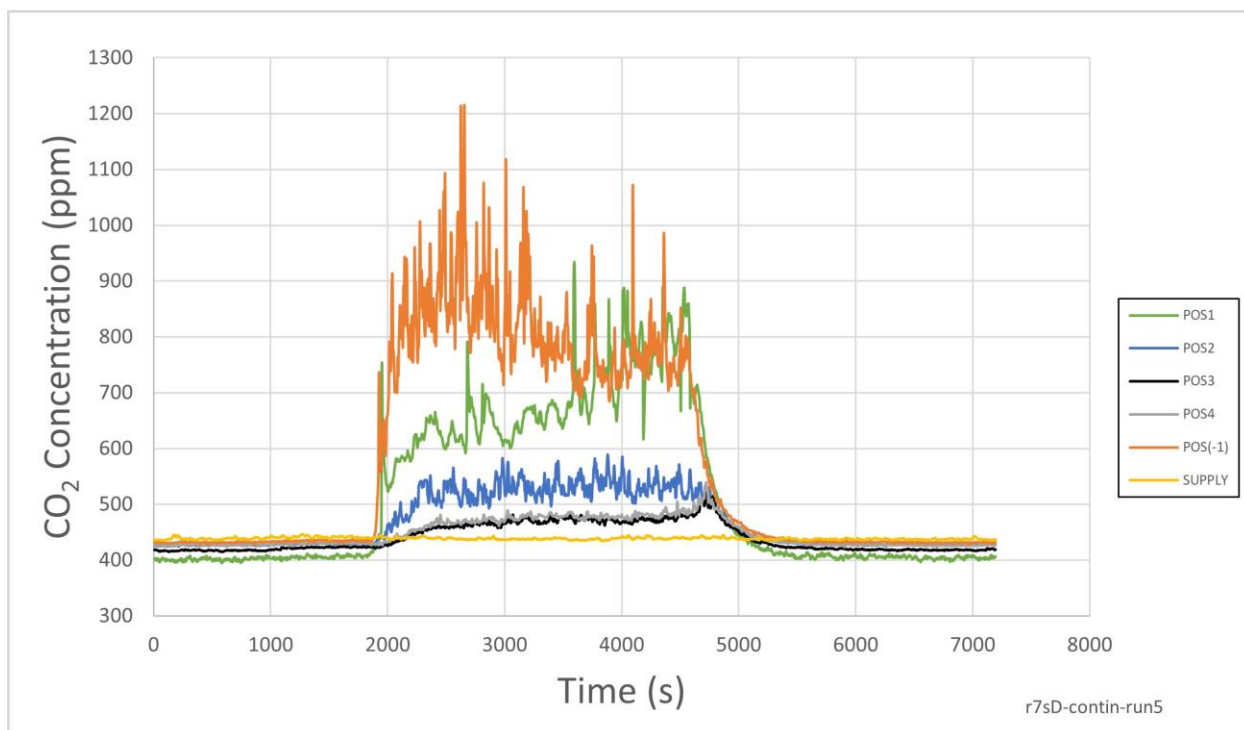


Figure 6.4: Row 7 Seat D Continuous Injection, Run 4

These shifts are unpredictable, and occur less than the “typical” response. Another important observation that is present in nearly all tests performed, not just in the Row 7 Seat D Continuous runs, is that the largest response occurs as the POS(-1) location, or the seat directly behind the injection source. As it occurs in nearly all test results, it is indicative of a slight rearward current overall in the 767 mockup cabin.

6.2.1.2: 1-Minute Puff Injection

The 1-minute puff injection response shows a unique behavior amongst the set, comparable to the 3-minutes puff. The “typical” response, seen in Figure 6.5 and Figure 6.6, from the 1-minute puff is a sharp rise in carbon dioxide concentrations at the POS1 and POS(-1) locations, with the POS(-1) location having the greatest response overall in the majority of tests. However, the POS1 location did at times have a peak carbon dioxide concentration as high as that of POS(-1), and occasionally went higher, as seen in Figure 6.7 and Figure 6.8.

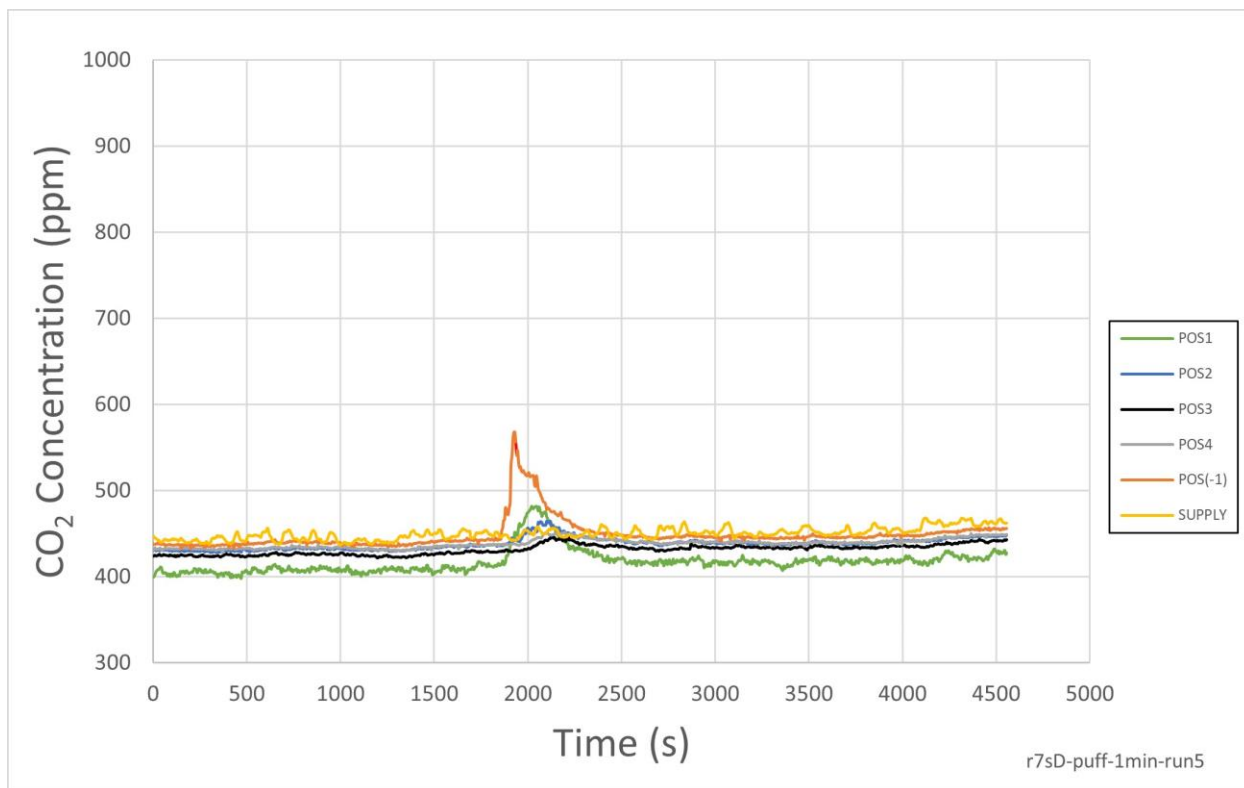


Figure 6.5: Row 7 Seat D 1-Minute Puff Injection, Run 4

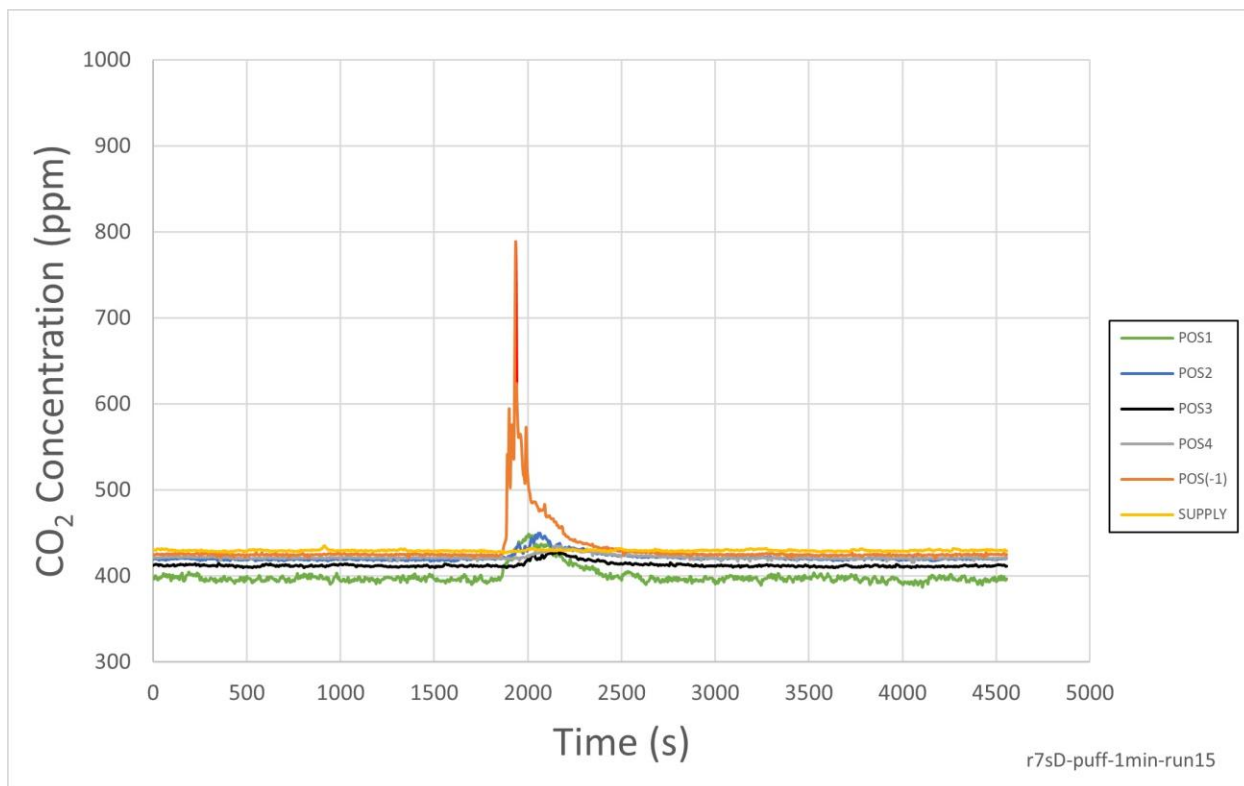


Figure 6.6: Row 7 Seat D 1-Minute Puff Injection, Run 12

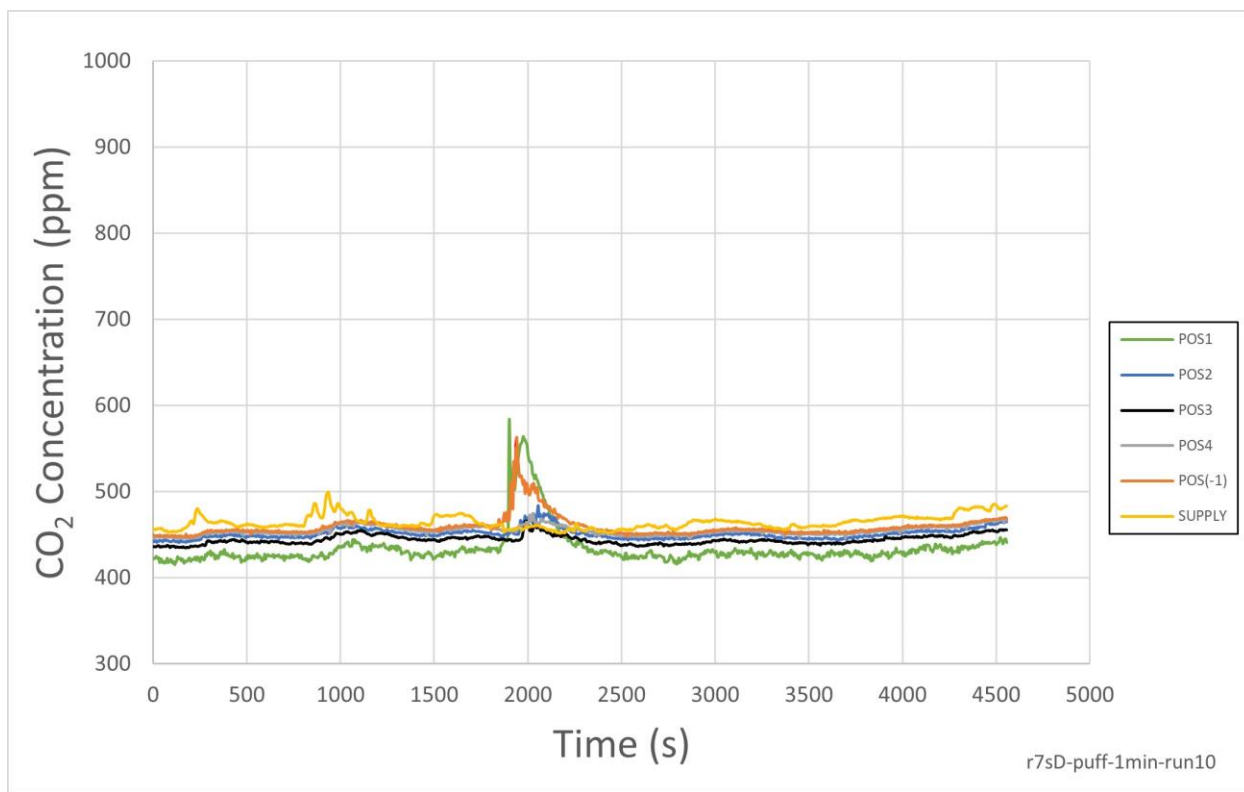


Figure 6.7: Row 7 Seat D 1-Minute Puff Injection, Run 8

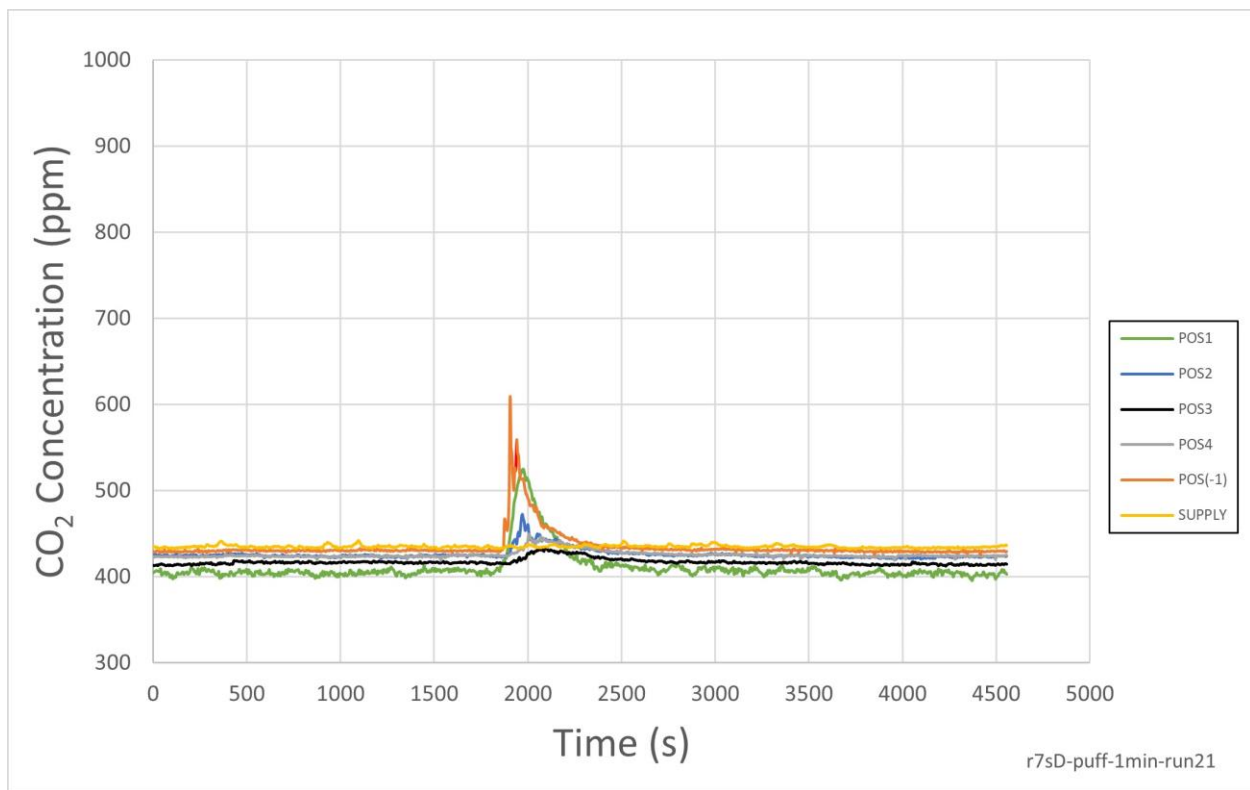


Figure 6.8: Row 7 Seat D 1-minute Puff Injection, Run 18

Figure 6.5 and Figure 6.7 are also good examples of the necessity of the ambient supply air offset in the percent relative exposure calculations; looking closely at Figure 6.7 one can see how the carbon dioxide (ppm) concentrations at each position fluctuate in response to the incoming ambient supply air, as well as to the injection itself. Using an offset in the percent relative exposure reductions mitigate errors propagated by these responses to the ambient supply air.

6.2.1.3: 3-Minutes Puff Injection

The 3-Minutes Puff Injection tests show a very similar response graph per result as the 1-Minute Puff Injections, but with some key differences. The peaks of the 3-Minutes puff tests are higher on average for the set, per position, as seen in Figure 6.9, Figure 6.10, Figure 6.11, and Figure 6.12. Figure 6.11 and Figure 6.12 have some fluctuation in the ambient supply air, again

highlighting the need for offset. There were also fewer recorded instances of the POS1 sensor recording a peak ppm value higher than that of the POS(-1) sensor location.

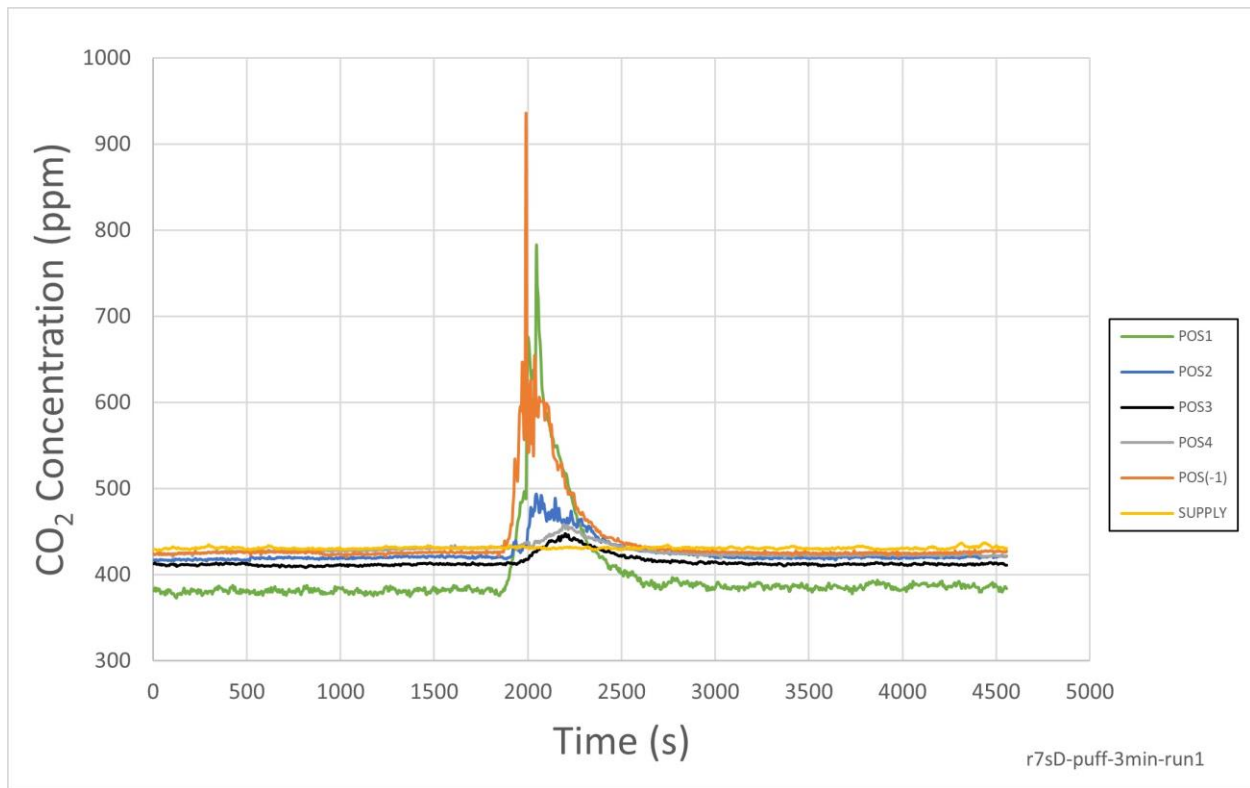


Figure 6.9: Row 7 Seat D 3-Minutes Puff Injection, Run 1

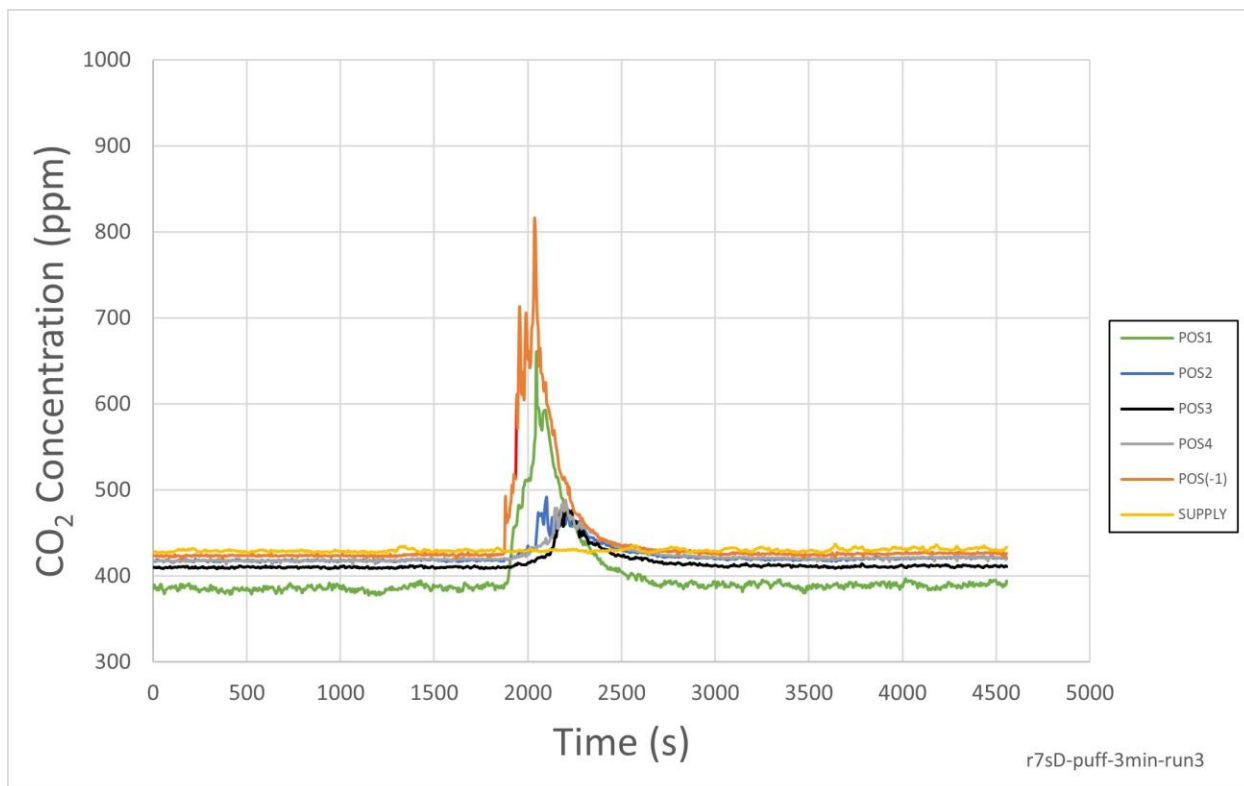


Figure 6.10: Row 7 Seat D 3-Minutes Puff Injection, Run 3

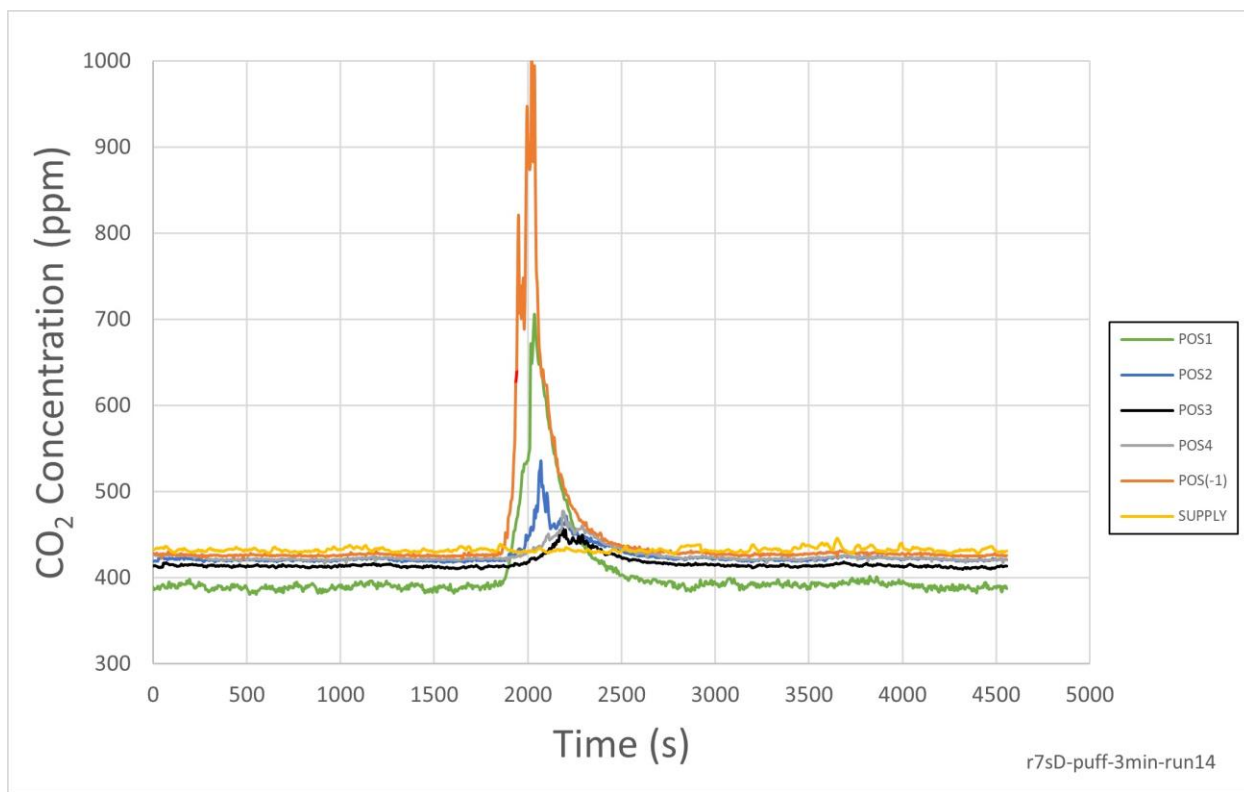


Figure 6.11: Row 7 Seat D 3-Minutes Puff Injection, Run 14

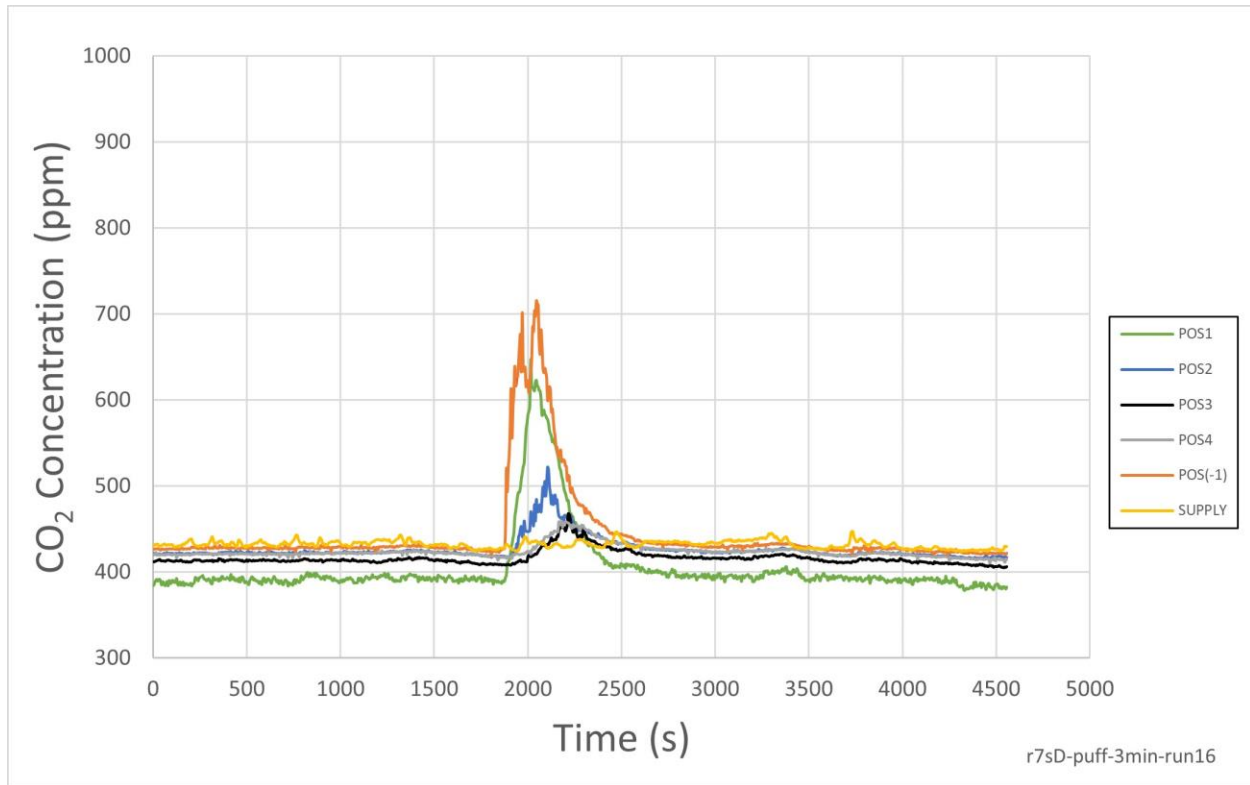


Figure 6.12: Row 7 Seat D 3-Minutes Puff Injection, Run 16

6.2.2: Row 7 Seat G

The tests conducted at Row 7 Seat G show some similarities in the results from Row 7 Seat D, but show unique behavior that set them apart.

6.2.2.1: Continuous Injection

The continuous injection tests for Row 7 Seat G (the right window seat of row 7) presented some unique peculiarities early on as the preliminary results were not in line with what had previously been observed at Row 7 Seat D, and thus required further investigation. After verifying that the supply air flowrate was unchanged and that the tracer gas flowrate being injected was correct through using an electronic pressure transducer and Arduino unit for recording, testing proceeded as planned. The differences in the results are not associated with

testing procedures, measurement procedures, or data reduction techniques. This topic will be discussed further in 7.1.1: Continuous Injection.

The set of continuous injection tests present much of the same chaotic nature in the responses per location, but are much lower overall than their Row 7 Seat D counterparts, as seen in Figure 6.13, Figure 6.14 and Figure 6.15.

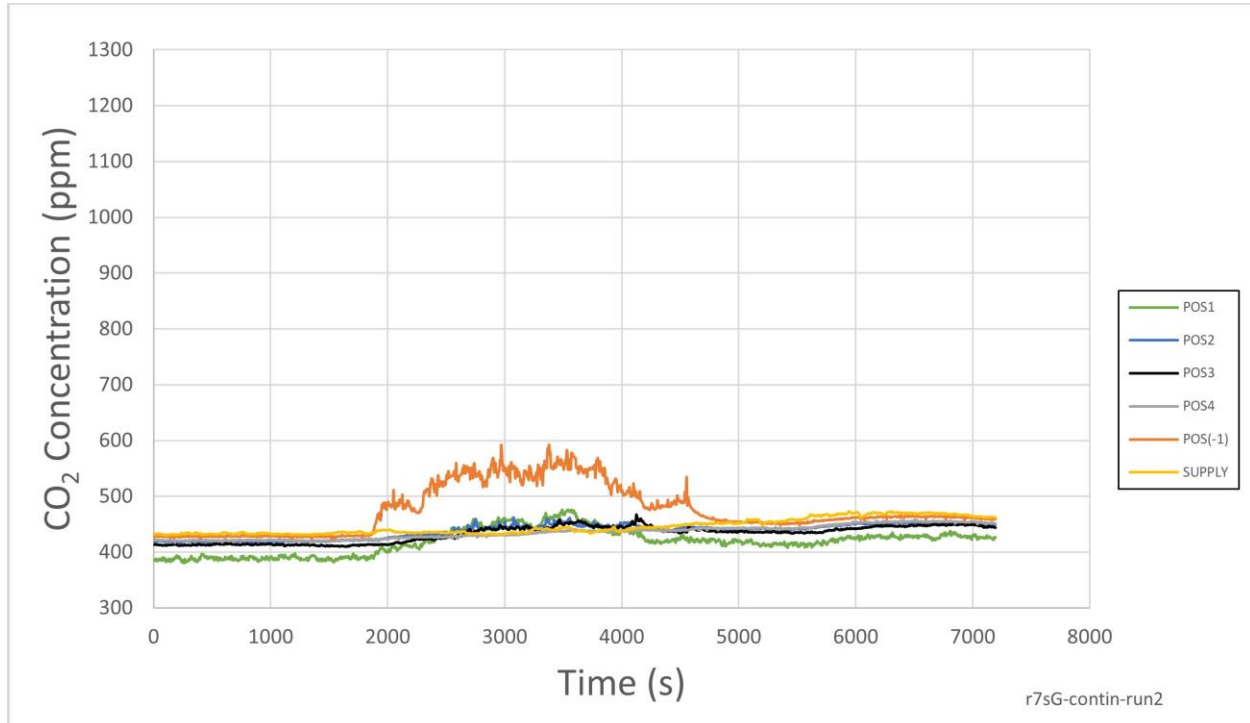


Figure 6.13: Row 7 Seat G Continuous Injection, Run 2

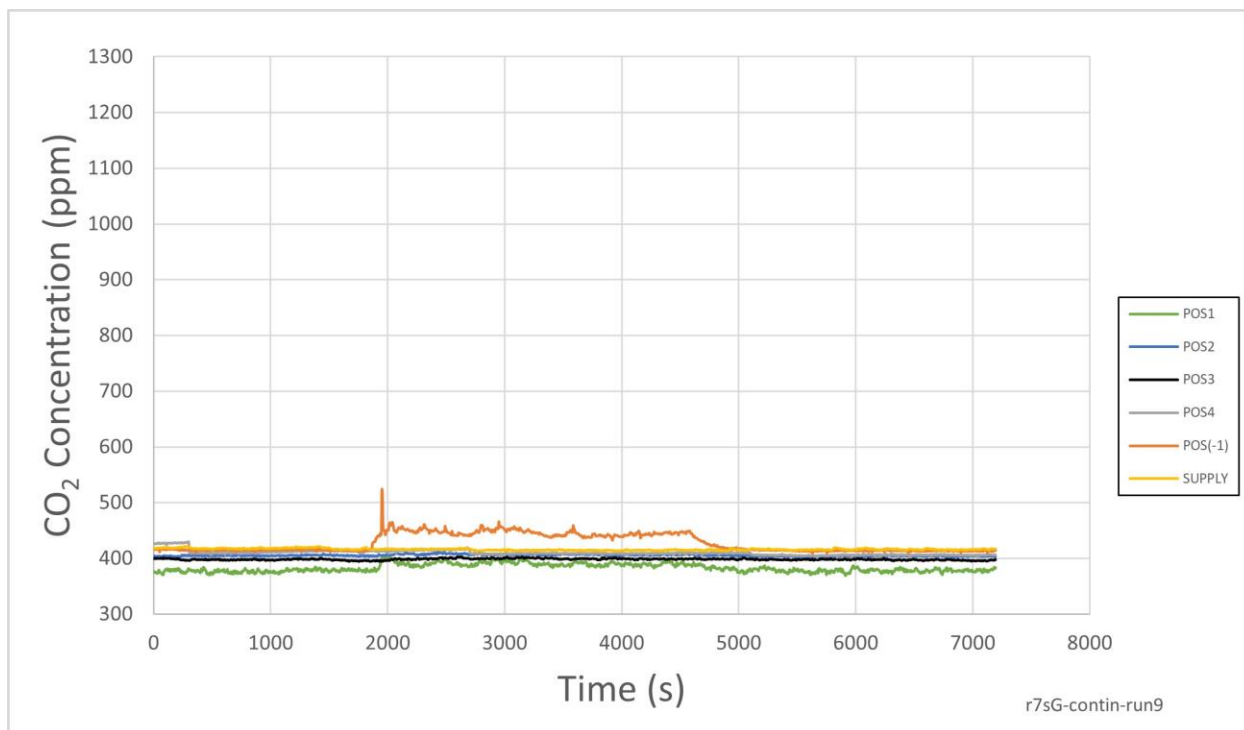


Figure 6.14: Row 7 Seat G Continuous Injection, Run 9

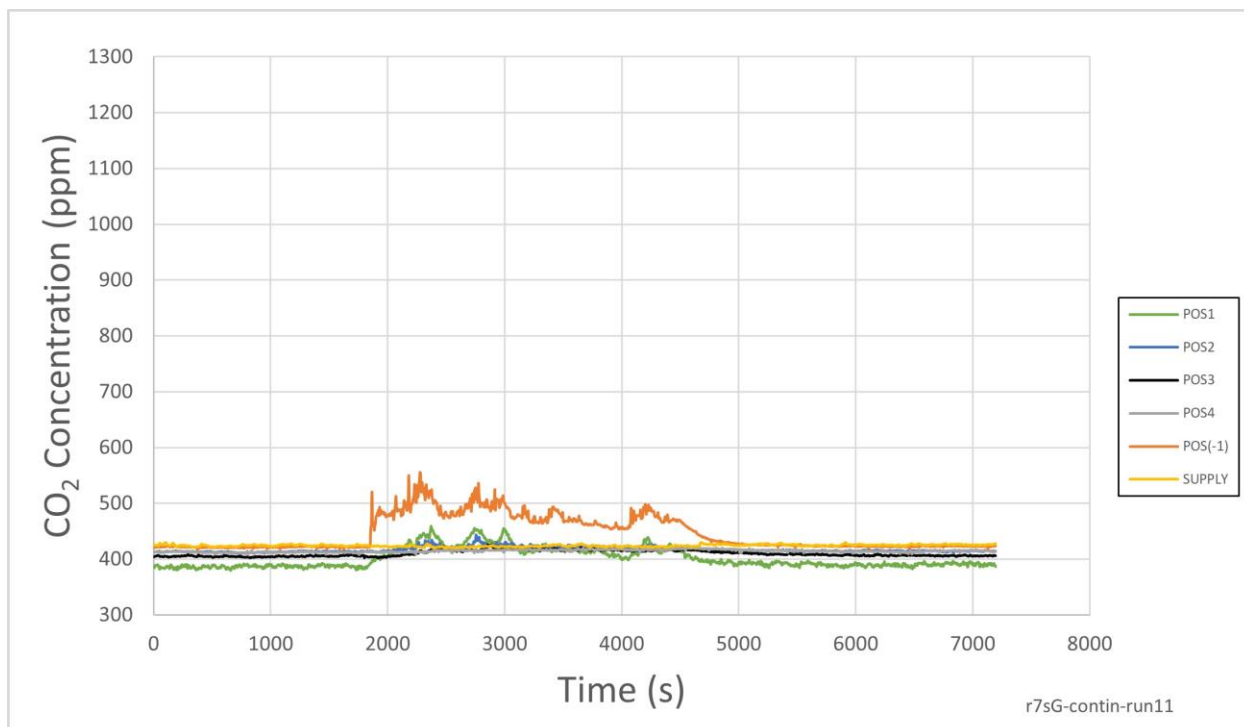


Figure 6.15: Row 7 Seat G Continuous Injection, Run 11

Further, there is a higher degree of variability in the responses. The behavior of large swings in response evident and pointed to in the Row 7 Seat D discussion is more noticeable in the Row 7 Seat G results, as seen in Figure 6.15, and in Figure 6.16 and Figure 6.17.

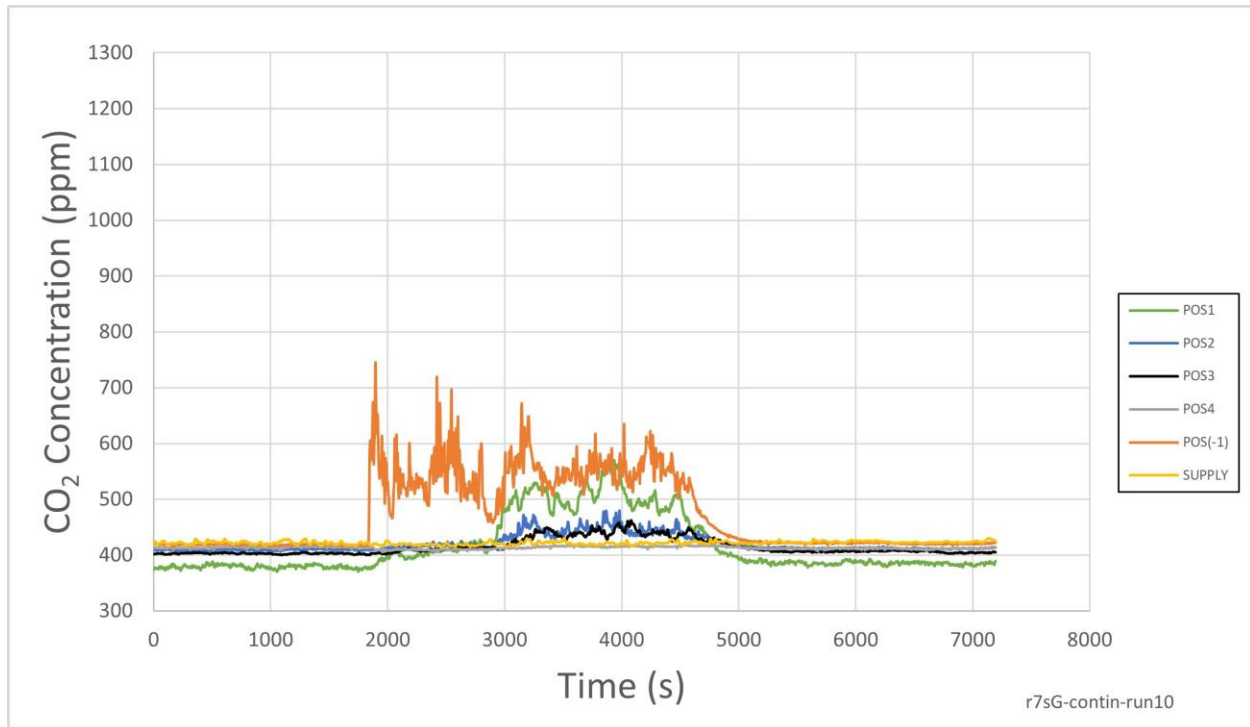


Figure 6.16: Row 7 Seat G Continuous Injection, Run 10

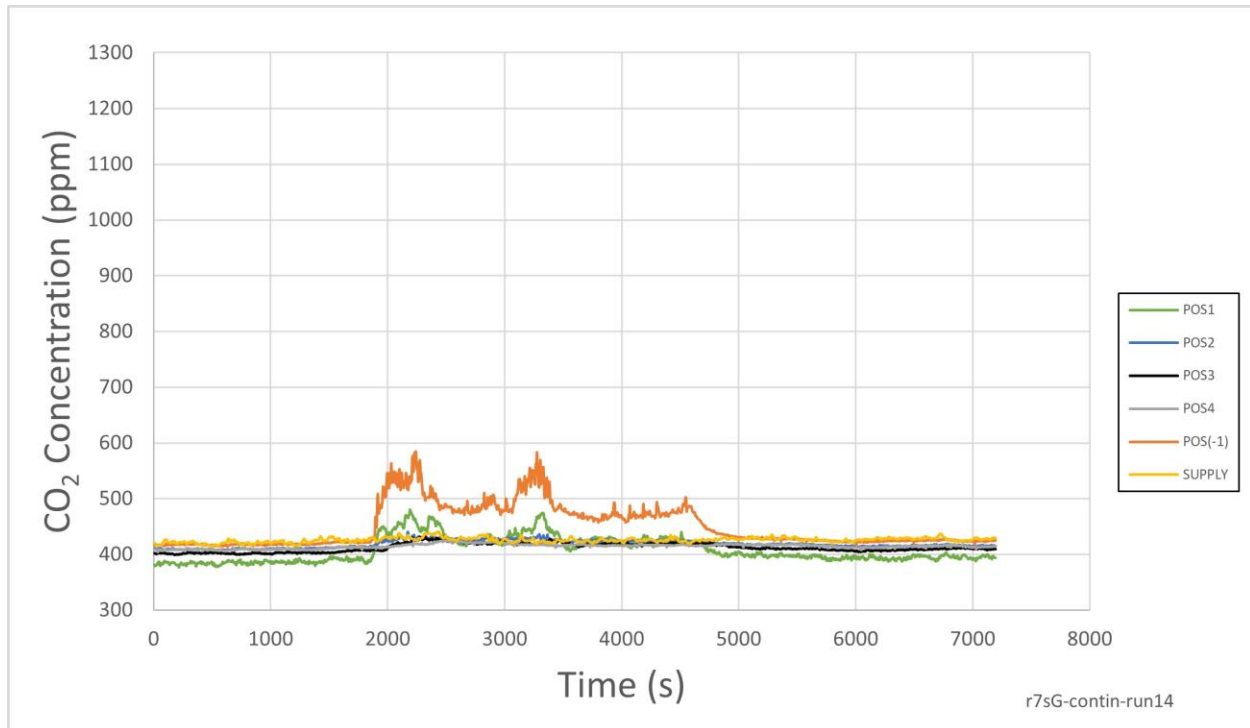


Figure 6.17: Row 7 Seat G Continuous Injection, Run 14

6.2.2.2: 1-Minute Puff Injection

The 1-Minute Puff Injection set of results for Row 7 Seat G are similar to those from Row 7 Seat D in their overall response, as seen in Figure 6.18 and Figure 6.19 and Figure 6.20. The ambient supply air shows the same chaotic nature, validating the use of the offset, as described previously.

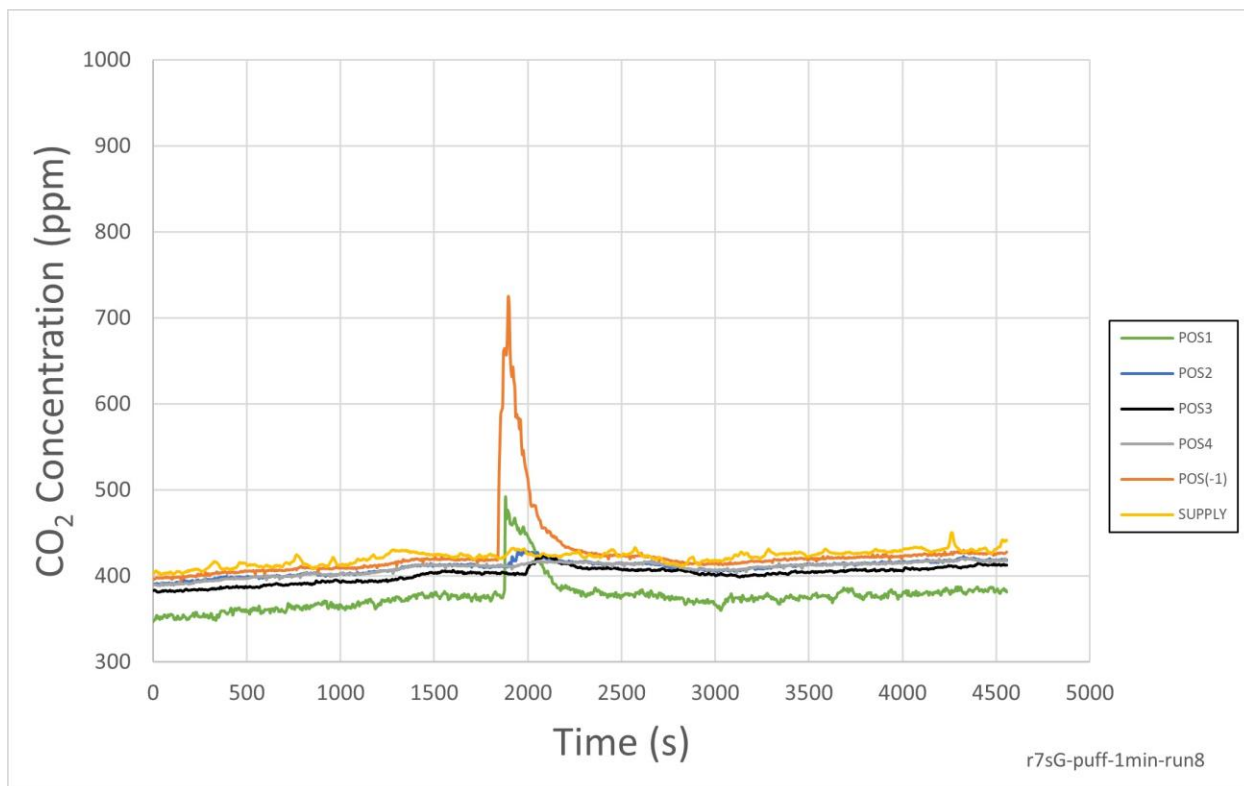


Figure 6.18: Row 7 Seat G 1-Minute Puff Injection, Run 6

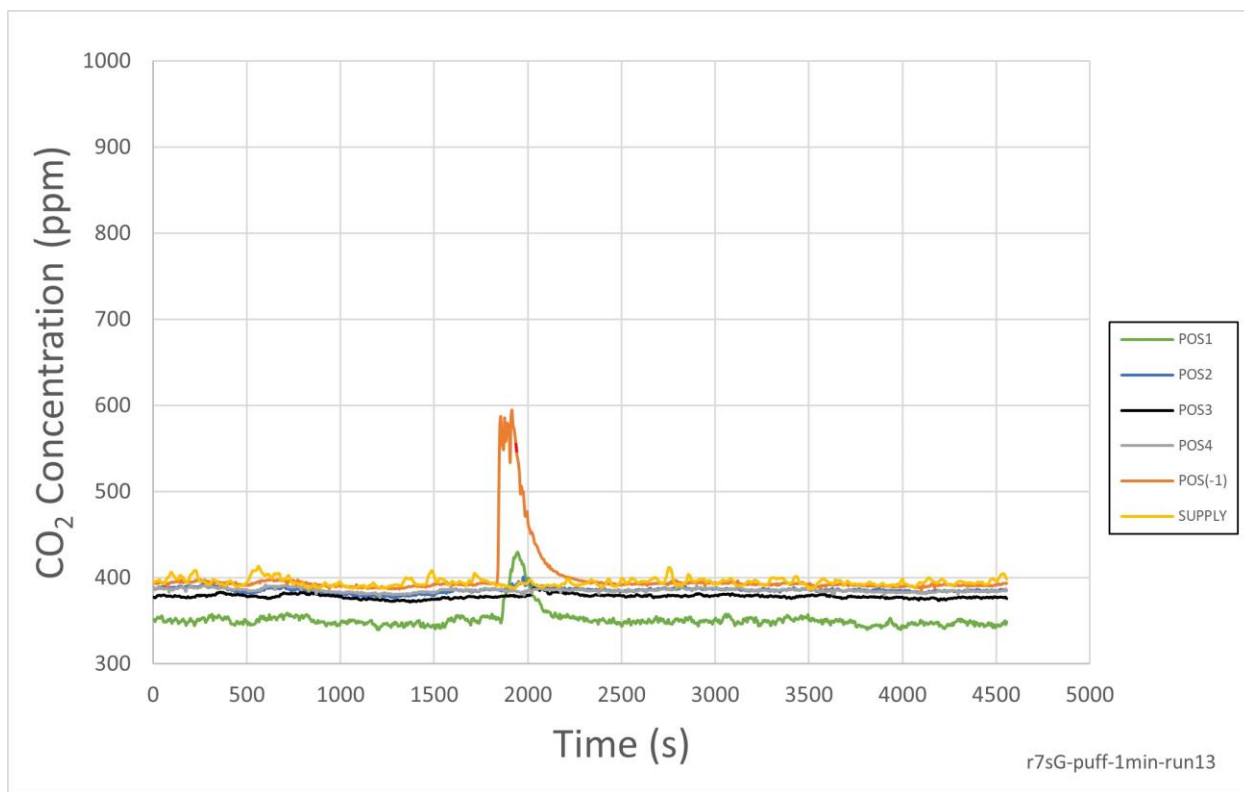


Figure 6.19: Row7 Seat G 1-Minute Puff Injection, Run 11

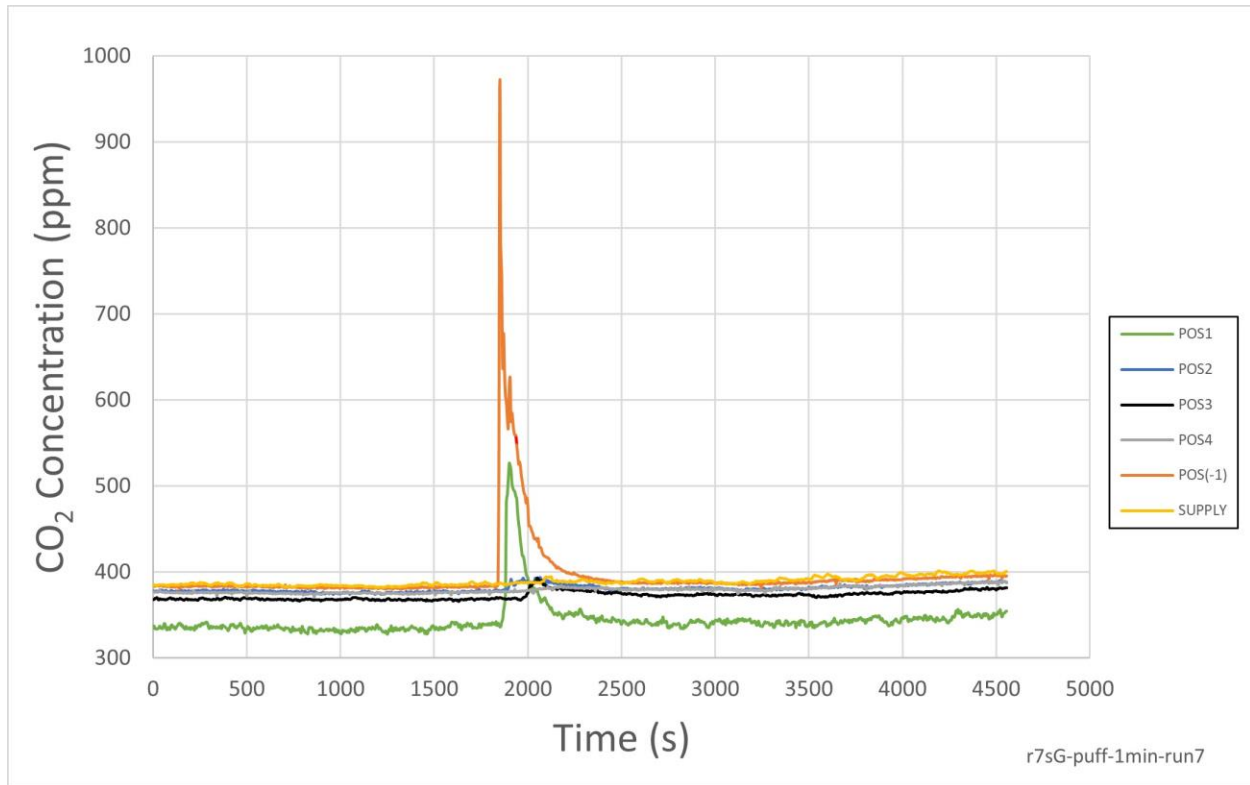


Figure 6.20: Row 7 Seat G 1-Minute Puff Injection, Run 5

6.2.2.3: 3-Minutes Puff Injection

The results for the 3-Minutes Puff Injection tests for Row 7 Seat G are similar in response to those at Row 7 Seat D, as seen in Figure 6.21, Figure 6.22, and Figure 6.23. Numerically, with regard to relative exposure percentage, they are different; these results for all injection types will be discussed further in Chapter 7. As in Row 7 Seat D, these 3-Minutes Puff Injections show the greatest response at the POS(-1) and POS1 locations. Their duration is also greater when compared to that of the 1-Minute Puff Injection results, with the average (per test) peak concentrations being greater as well.

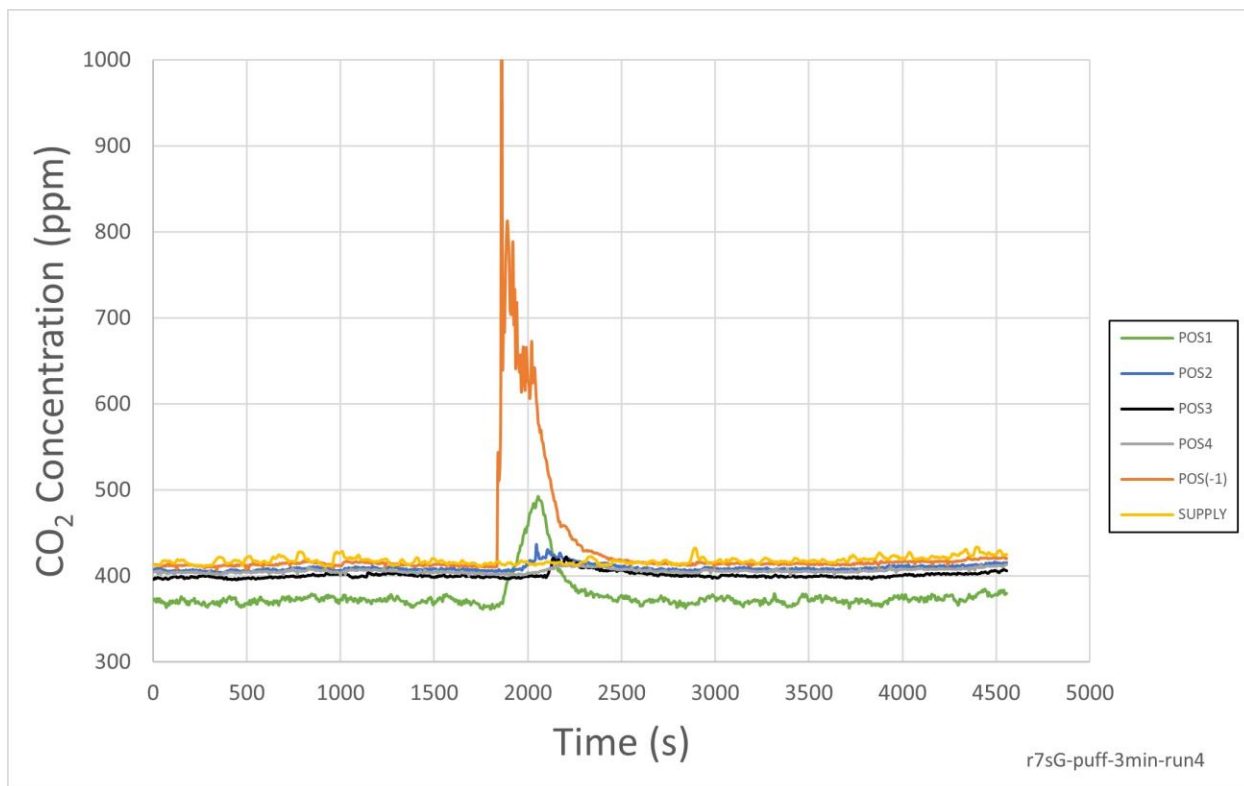


Figure 6.21: Row 7 Seat G 3-Minutes Puff Injection, Run 4

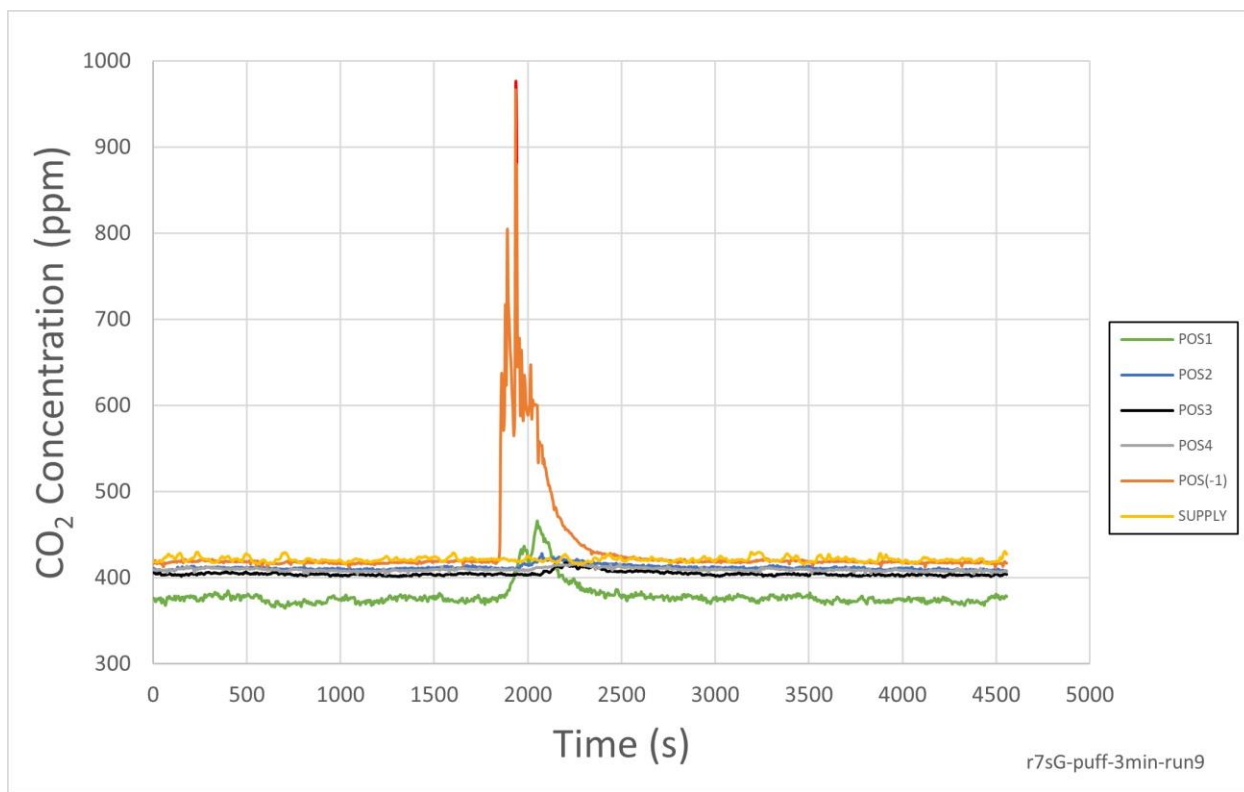


Figure 6.22: Row 7 Seat G 3-Minutes Puff Injection, Run 9

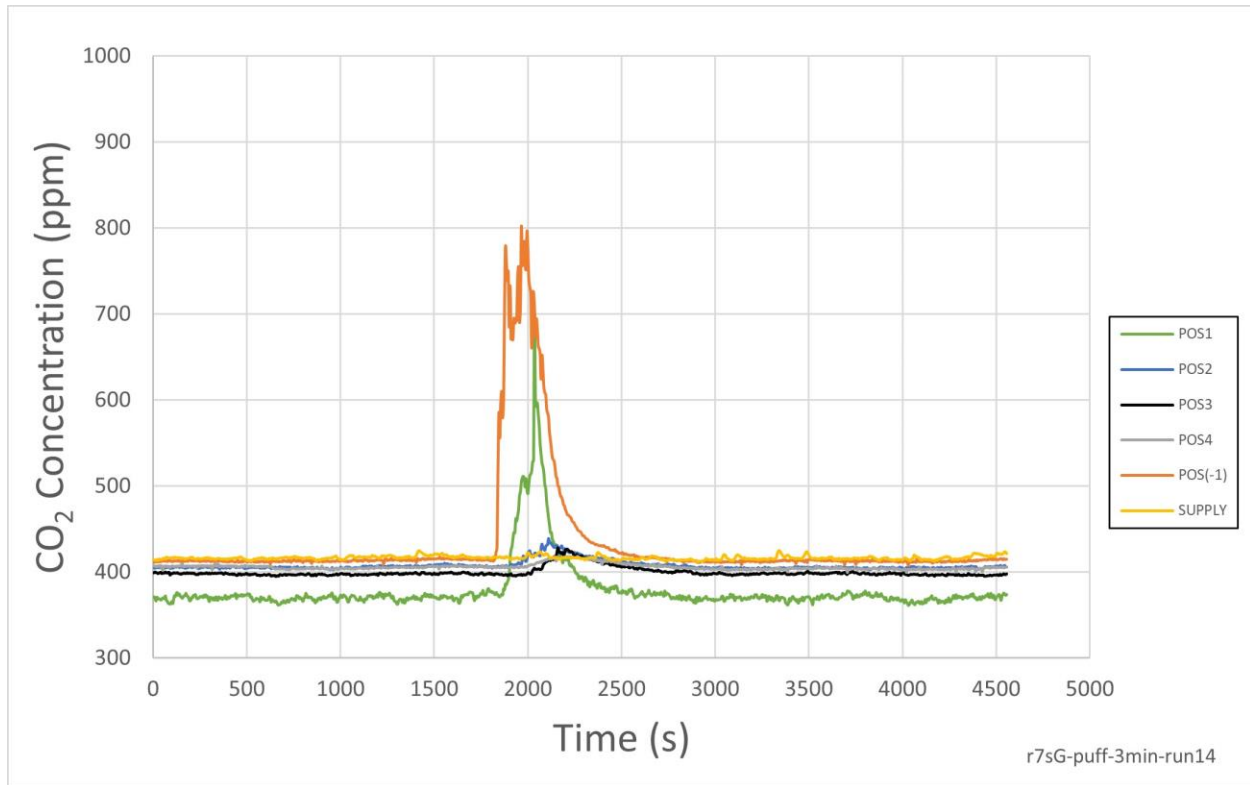


Figure 6.23: Row 7 Seat G 3-Minutes Puff Injection, Run 14

Chapter 7 - Results and Discussion

The graphical representation of the results presented in Chapter 6 are necessary for a more complete understanding of the quantitative approach of this chapter. The end result of each test is the calculation of the *percent relative exposure*, which as a reminder, is taken broadly as the fraction of additional carbon dioxide that would be inhaled by an occupant at the specified location over the total carbon dioxide injected into the cabin. This chapter is almost exclusively directed at the analysis of the results of all percent relative exposures calculated over the 123 tests. The results are grouped by testing location, and presented individually (for each injection type) as well as in combined fashion to further elucidate the dynamics of each testing location, and the overall implications of the findings.

7.1: Row 7 Seat D

Row 7 Seat D was chosen as a representative location to test at due to its central location in the cabin, and prior testing at that location (see Mahmoud, 2021 and Shehadi, 2015).

7.1.1: Continuous Injection

The raw data, presented in percent relative exposure, is shown here in Figure 7.1. The graph presents each sensor location, with accompanying single sample standard deviation bounds (black bars) and average (green data point). What is immediately evident is the rearward biased distribution of percent relative exposure; that is the sensor location behind the injection source, POS(-1), is consistently higher than that of the position in front of the injection source, POS1. What's more, POS2 and POS3 are successively lower in distribution and mean, i.e. POS1 is greater than POS2, and POS2 is greater than POS3. The mean percent relative exposure for POS4 is very slightly larger than POS3.

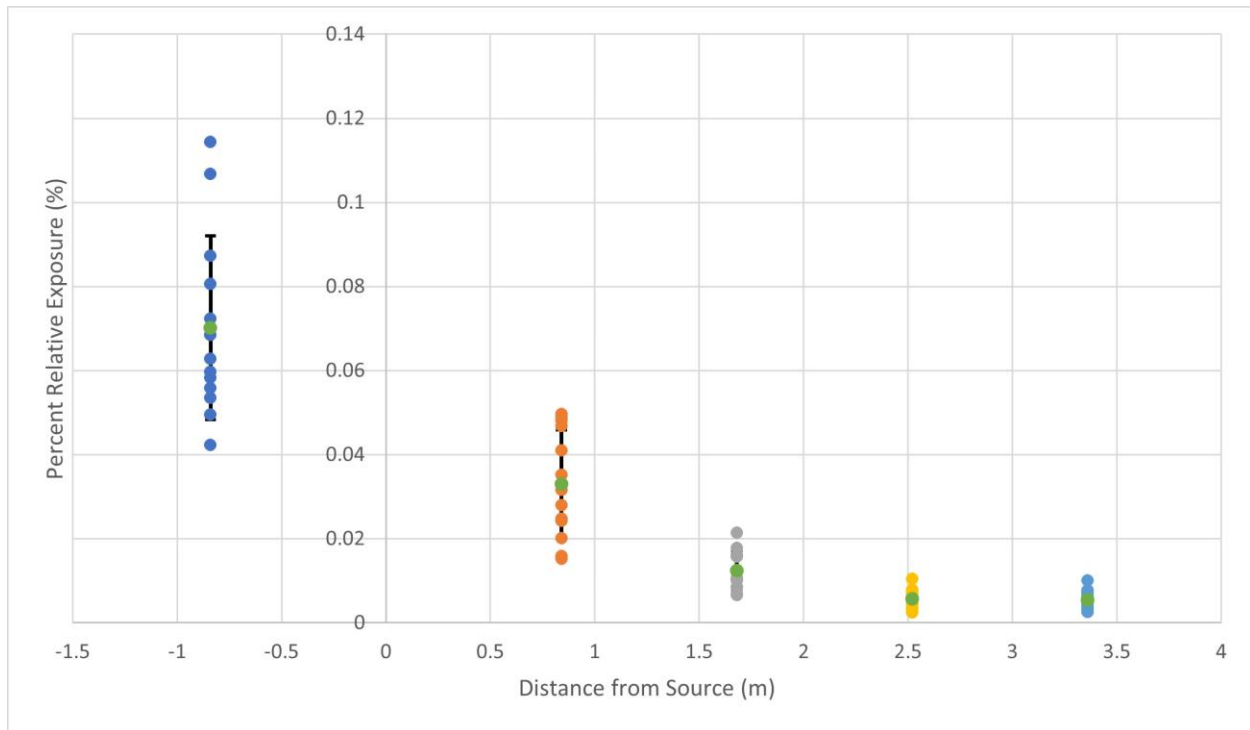


Figure 7.1: Row 7 Seat D Continuous Injection Raw Data

7.1.2: 3-Minutes Puff Injection

The 3-Minutes Puff Injection raw data, shown in Figure 7.2 and presented in the same format as Figure 7.1, shows a similar trend to that of the Continuous Injection, that is the mean and distribution for POS1 to POS4 are successively smaller the farther from the source, with POS4 being slightly larger than POS3.

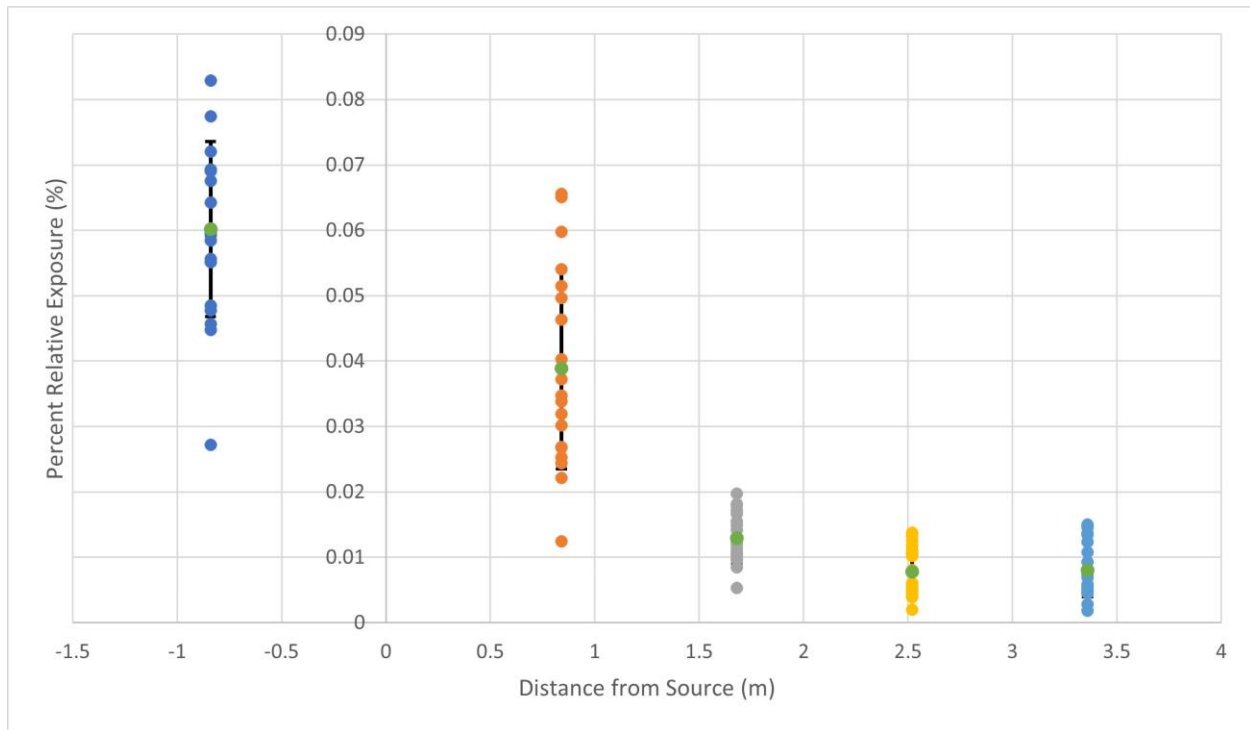


Figure 7.2: Row 7 Seat D 3-Minutes Puff Injection Raw Data

7.1.3: 1-Minute Puff Injection

The 1-Mintue Puff Injection results also show the same trend as in the Continuous Injection and 3-Minutes Puff Injection, and are presented in the same format in Figure 7.3.

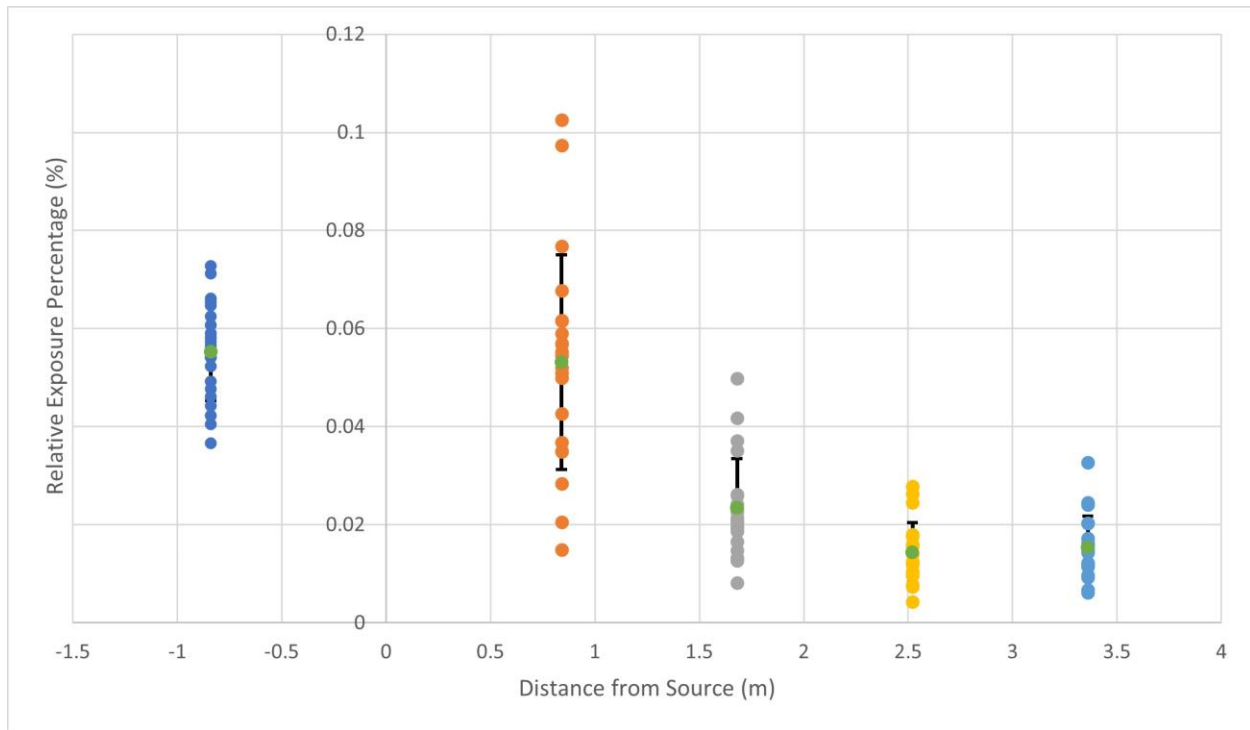


Figure 7.3: Row 7 Seat D 1-Minute Puff Injection Raw Data

7.1.4: Combined Analysis

When taken together, the results show a clearer picture of the nature of the physical system at work. The comparison for raw data of all 3 testing regimes, shown in Figure 7.4, is presented in pseudo-location form, that is the positions are grouped together, but the true distances from the source should be ignored. Looking at all three injection types side-by-side-by-side, a clearer picture begins to emerge. The relationship between the three, in the positive direction (POS1 to POS4), is seen as the 1-Minute Puff has a higher mean per location than the 3-Minute, and the 3-Minute has a higher mean per location than the Continuous. Thus, there is a distinct delineation from the 1-Minute to the 3-Minute to the Continuous, with the 3 Minute results falling in between the 1-Minute and the Continuous results, respectively. This is true for all but the POS(-1) location behind the injection source. This relationship is perhaps better illustrated in Figure 7.5, which is presented as only the combined means with accompanying

curves. Perhaps what is most interesting from these findings is the inverted nature of POS(-1), where the Continuous mean is greater than the 3-Minute mean, and the 3-Minute mean is greater than the 1-Minute mean. All means at POS(-1) are larger than the means at POS1, further showing the rearward trend in the dispersion. When Figure 7.5 was first discussed, it was decided that another calculation be added. Figure 7.6 shows the combined means for each injection type, and the error bars reflect 2 standard deviations *of the mean*, or the 95% confidence interval. The 95% Confidence Interval for the mean is calculated as:

$$95\% CI = 2 \cdot \frac{\sigma_{sample}}{\sqrt{n-1}} \quad (7)$$

Where σ_{sample} is the standard deviation of the sampled location data, and n is the size of the sample. The purpose of this calculation is to determine if the confidence for the means for each location for all 3 injection types overlap. The results and implications of Figure 7.6 (for Row 7 Seat D) are discussed along with the results in Figure 7.12 (for Row 7 Seat G) in 7.2.4: Combined Analysis.

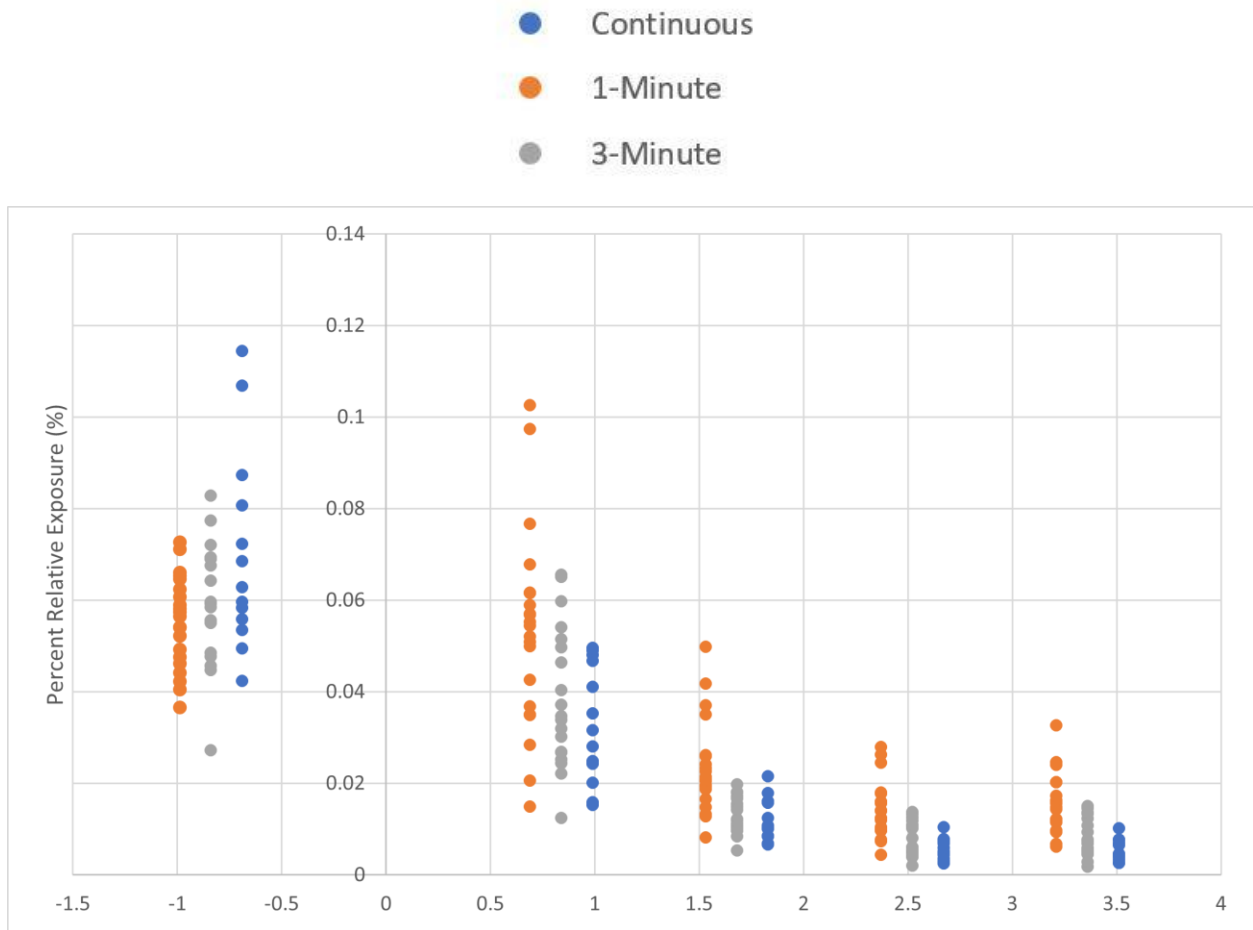


Figure 7.4: Row 7 Seat D Combined Raw Data

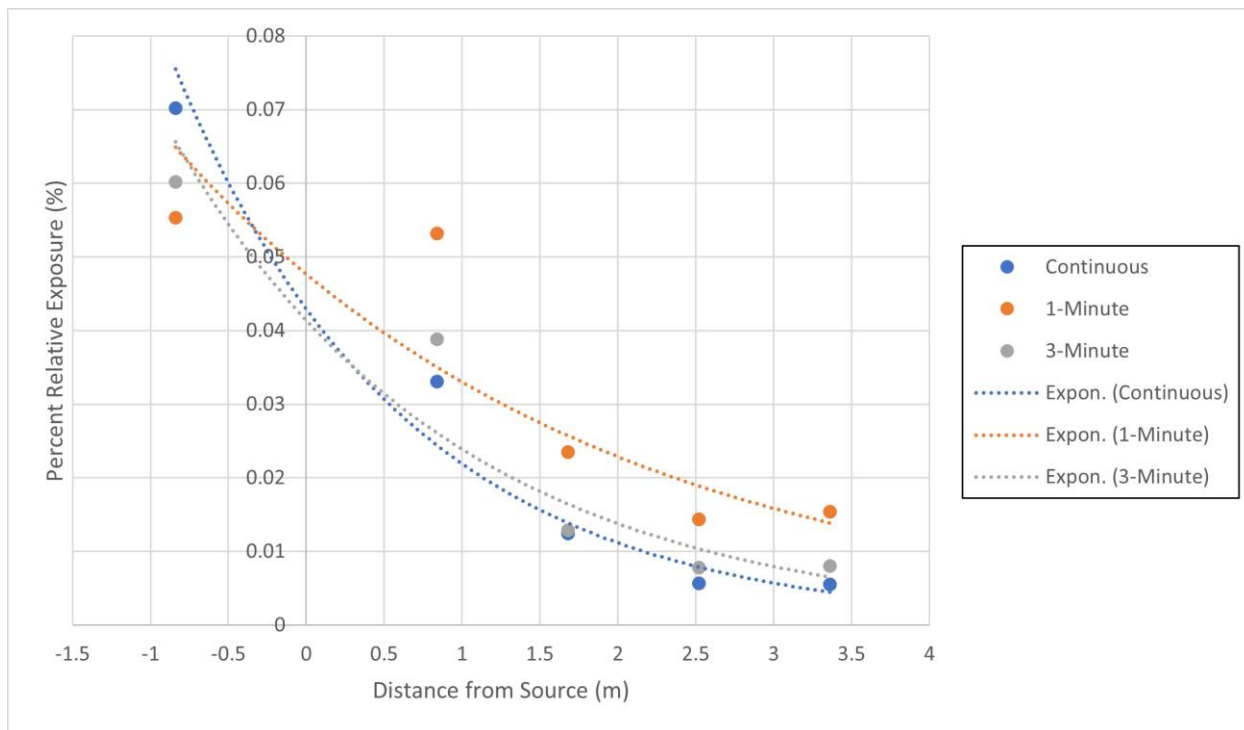


Figure 7.5: Row 7 Seat D Combined Means

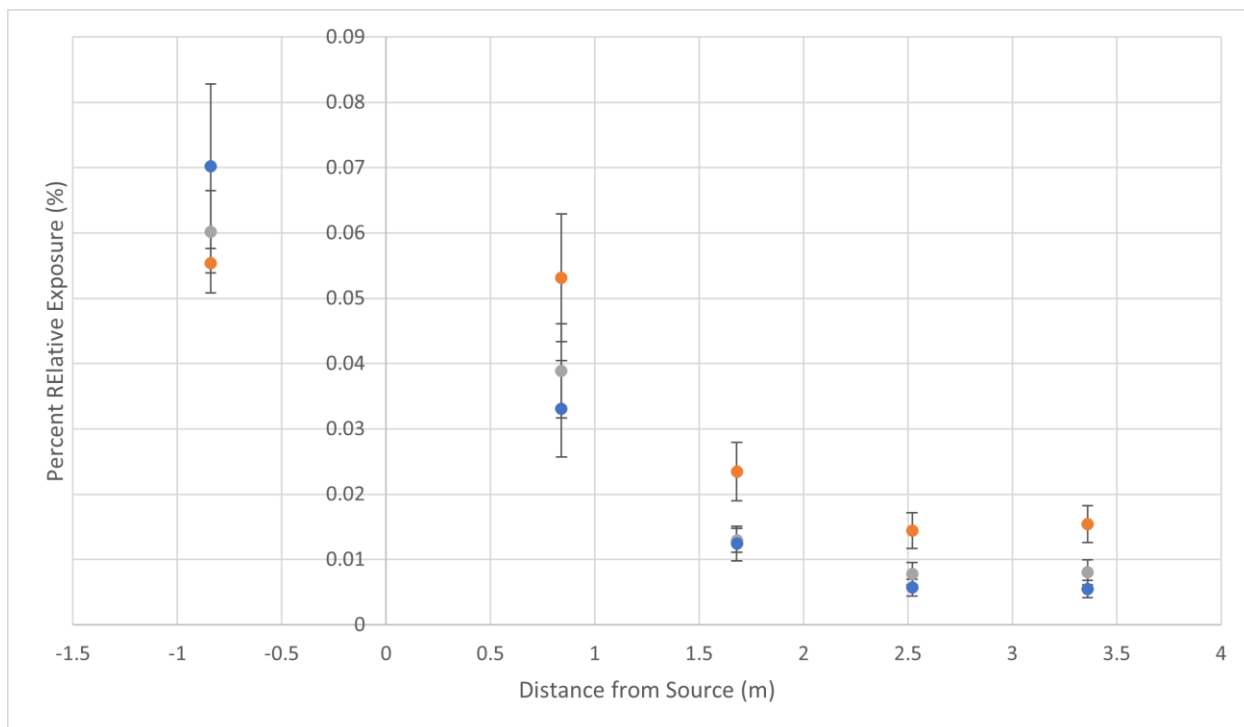


Figure 7.6: Row 7 Seat D Combined Means, Including 95% Confidence Interval

Row 7 Seat G was chosen due to it being a wall seat (window seat). It is the farthest seat in the row from the Seat D location, farthest seat from the diffusers, and as such was the most representative location for a testing location unique from Row 7 Seat D. The results for Row 7 Seat G are presented in the same order and form as those of Row 7 Seat D. The raw data graphs for each injection types are shown with the means at that location, in green, and with 1 standard deviation of the sample bounds, in black.

The Continuous Injection results for Row 7 Seat G are unique to the location, and markedly different than those of Row 7 Seat D:



While the trend in the distributions is the same, the value of the percent relative exposure is not. They are far less than their counterparts at Row 7 Seat D. However, the trend between the three forms of CO₂ injection seen at Row 7 Seat D is still present.

7.2.2: 3-Minutes Puff Injection

The 3-Minutes Puff Injection still shows a distribution pattern between sensor locations similar to its counterpart at Row 7 Seat D, as seen in Figure 7.8.

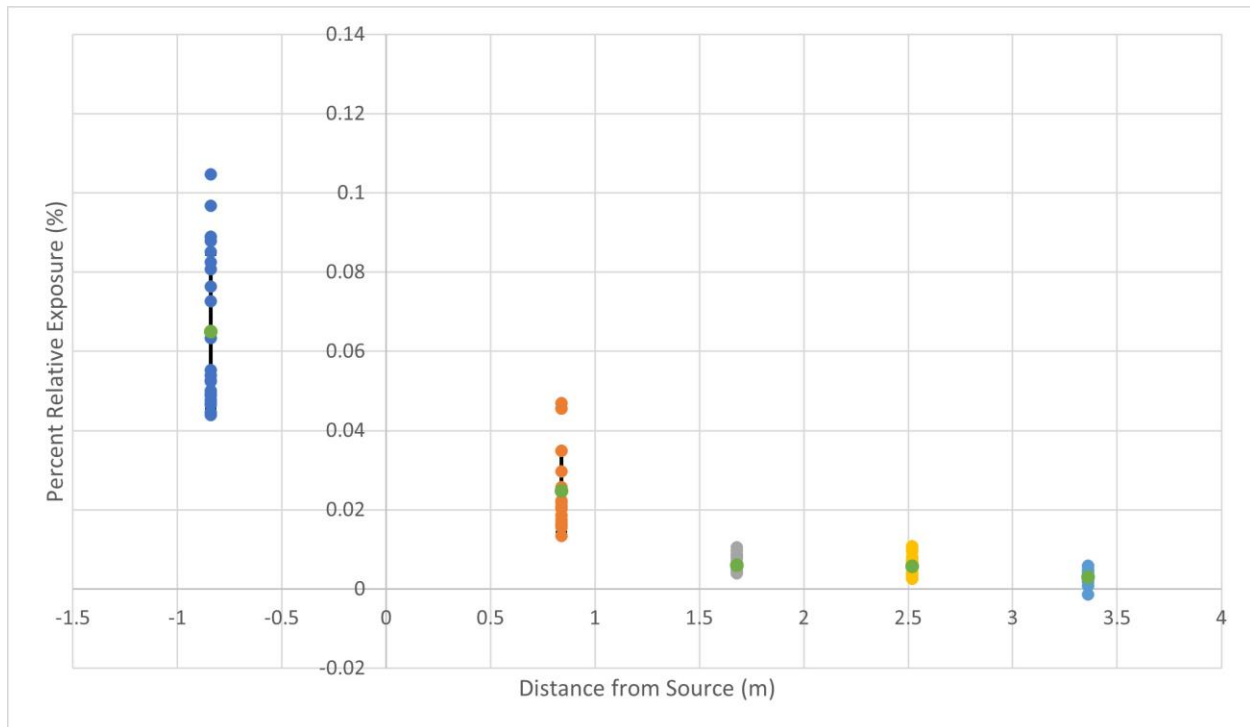


Figure 7.8: Row 7 Seat G 3-Minutes Puff Injection Raw Data

7.2.3: 1-Minute Puff Injection

The 1-Minute Puff Injection, seen in Figure 7.9, also shows a pattern between sensor locations similar to its counterpart at Row 7 Seat D.

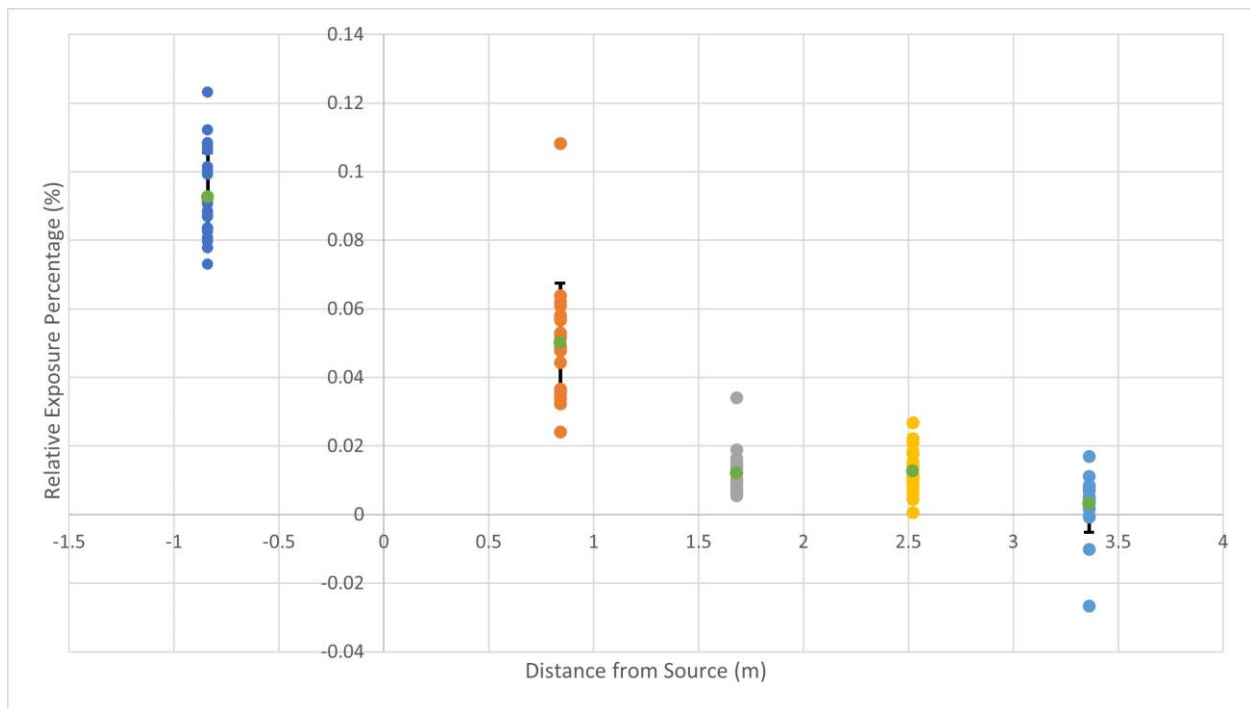


Figure 7.9: Row 7 Seat G 1-Minute Puff Injection Raw Data

7.2.4: Combined Analysis

Grouping them together in a pseudo-distance graphs, the relationship between the three injection types becomes more evident, shown in Figure 7.10. At POS1 through POS4, the relationship between the three injection types remains the same as their counterparts at Row 7 Seat D, as seen in Figure 7.4.

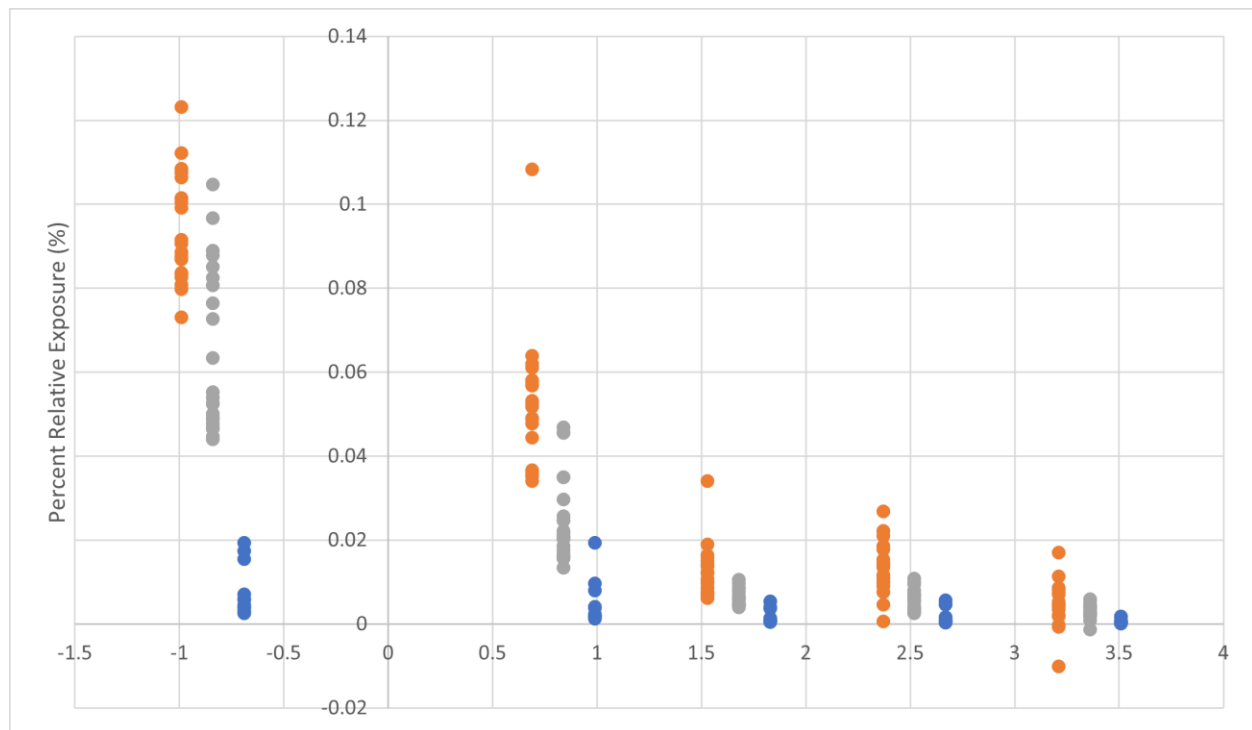


Figure 7.10: Row 7 Seat G Combined Raw Data

As it was in the results for Row 7 Seat D, the 3-Minutes Injection results are in between those of the 1-Minute Injection and Continuous Injection. While the relationship between the three forms of injection is the same for POS1 through POS4, it is reversed at POS(-1). At POS(-1) the 1 - Minute Injection has the greatest mean, followed by the 3-Minutes Injection, and finally the Continuous Injection, as opposed to the mean results for Row 7 Seat D. This pattern is more clearly seen in Figure 7.11, with the accompanying curves. In Figure 7.12 for the Row 7 Seat G results, most locations do not show overlap between confidence interval bounds. This indicates that there is greater than 95% certainty that the means differ not because of random chance. The converse is not true, which is important for the results of Row 7 Seat D in Figure 7.6: the overlap

and near overlap between bounds does not indicate that they are the same, it indicates that they are not statistically significantly different. Thus, it is unknown whether the difference is due to random chance or if they are indeed different.

The Continuous Injection results are perhaps the most striking in difference from those at Row 7 Seat D. While the rearward trend is still present, the overall dispersion is much lower, which has yet to be explained physically. Wall effects are potentially responsible for the low measured percent relative exposure values for the Continuous Injection; the closeness of the cabin wall may potentially be hindering proper spreading of the injection cloud. Only the Continuous Injection shows such a reduction in values compared to the Row 7 Seat D counterparts. At present there is no definitive physical explanation for this observed phenomenon. It has been speculated that some effect may be to the nature of the Continuous Injection type itself. The Continuous type

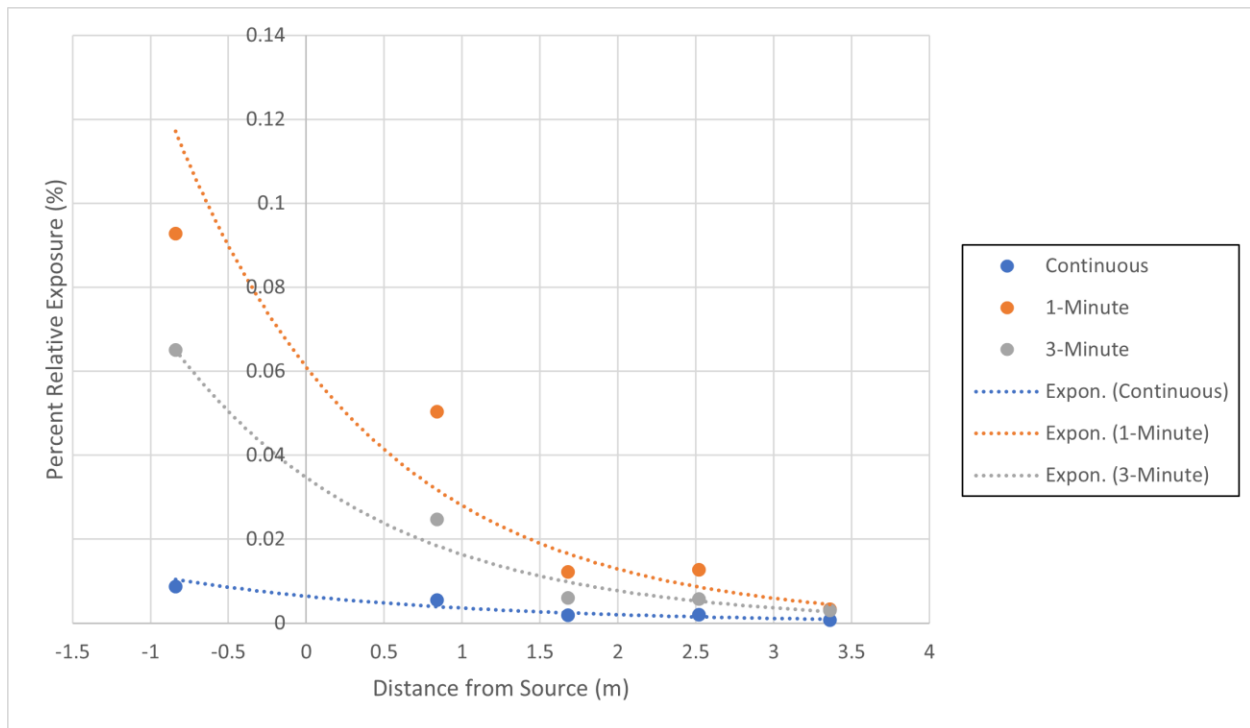


Figure 7.11: Row 7 Seat G Combined Means

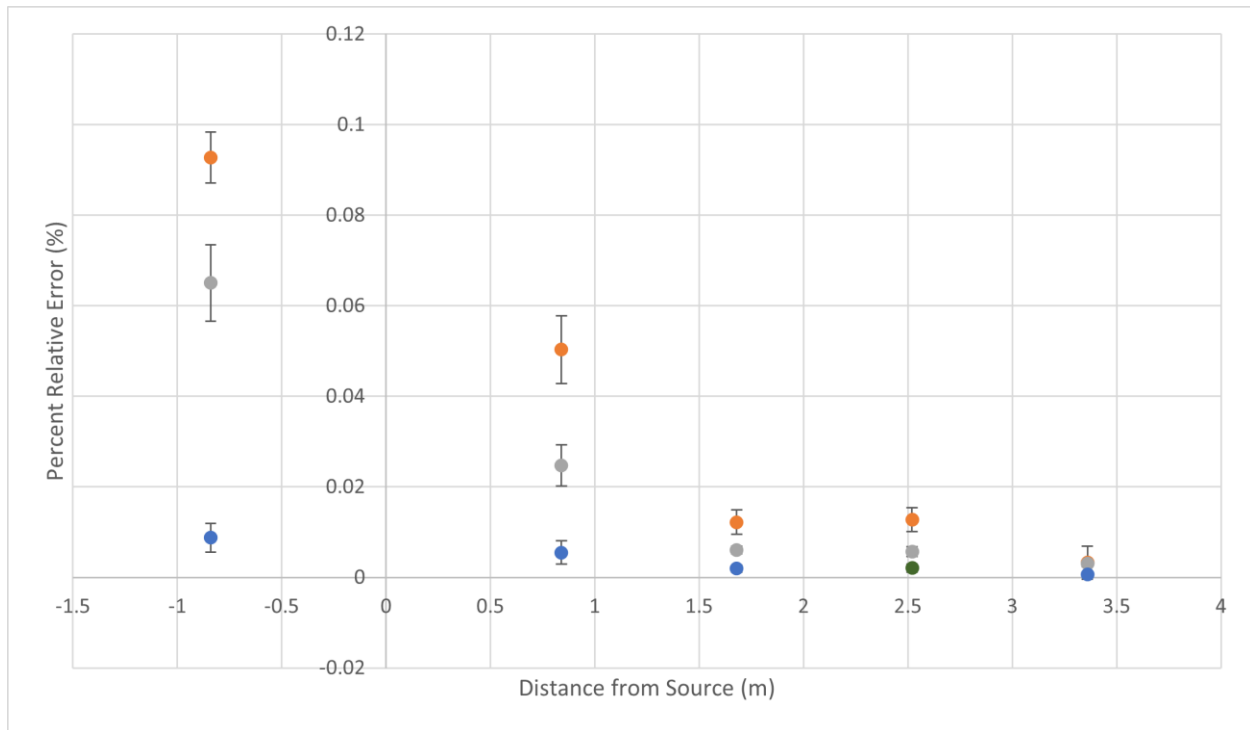


Figure 7.12: Row 7 Seat G Combined Means, 95% Confidence Interval

continually injects tracer gas into the cabin from the source, therefore it continually imparts momentum on the gas cloud (free jet) that is formed, unlike the 1-Minute and 3-Minute Puff Injection types, which only inject gas for 1 or 3 minutes respectively, and have much less momentum imparted into the gas cloud (free jet). The injection source is also mono-directional, meaning that the imparted momentum vector points upwards and only upwards. This effect, that of the mono-directionality of the injection, was tested directly in the Long Continuous Injection types with the use of a 5-Way T junction.

7.3: Long Continuous Injection

The Long Continuous Injection type was originally run as simply a time extension of the standard Continuous Injection, the results of which can be seen in 7.3.1: Row 7 Seat D and 7.3.2: Row 7 Seat G. The goal was to capture more of the unsteady effects (i.e., any large drifts) over a longer time period than were seen in the shorter time periods of the Continuous Injection; this is

why the Long Continuous Injection tests inject for 210 minutes rather than the 45 minutes of the standard Continuous Injection.

The use of the 5-Way T junction came about to answer the question of whether the injection port itself was having a jet effect on the tracer gas cloud; the tracer gas exits the source at 0.2631 m/s, with a volumetric flow rate of 8.0 SLM. By using the 5-way T-junction and splitting the volumetric flow rate 4 ways, a less narrow plume is generated, i.e., the injection has less momentum imparted only unidirectionally. Previous work at ACER has utilized the method of the injection port that faces upwards almost exclusively, and this present study followed the same protocols for the sake of consistency. In reality, on an aircraft where passengers are seated upright, breathing/coughing rarely occurs in only the upwards direction. Future experiments in the lab might consider utilizing a more realistic outwards approach to tracer gas injection.

7.3.1: Row 7 Seat D

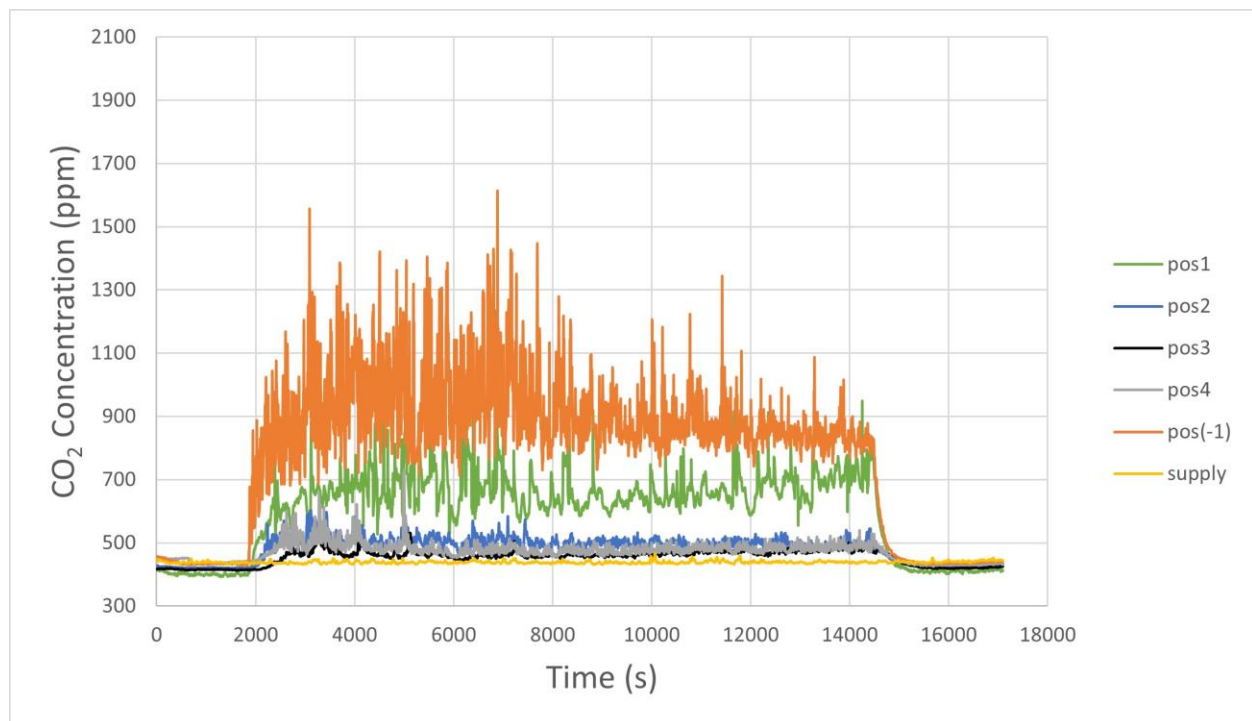


Figure 7.13: Row 7 Seat D Long Continuous, no T-Junction Run 1

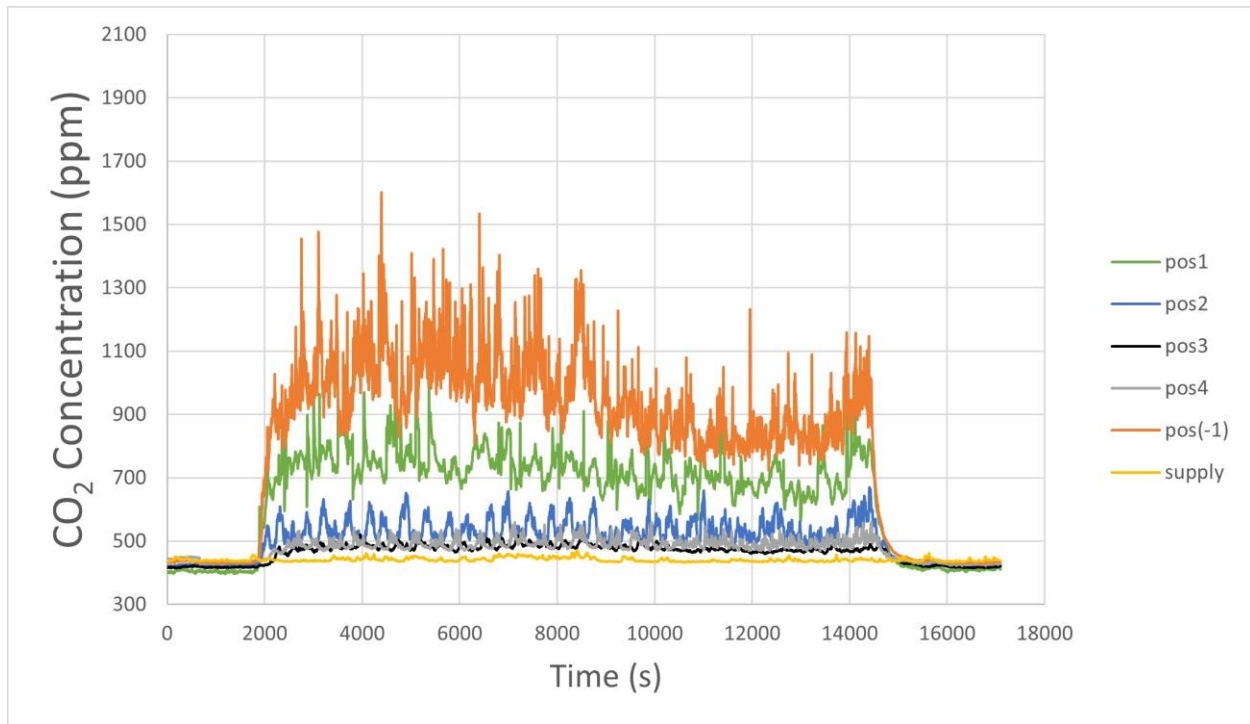


Figure 7.14: Row 7 Seat D Long Continuous, no T-Junction Run 2

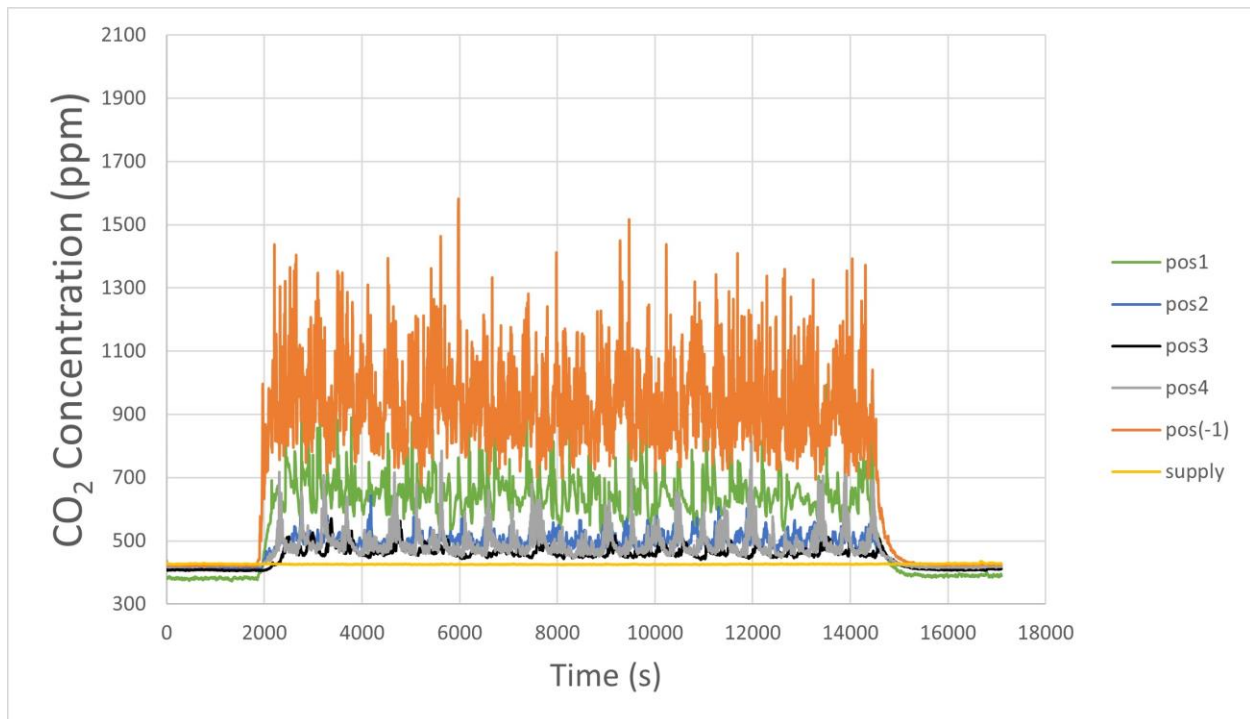


Figure 7.15: Row 7 Seat D Long Continuous, with T-Junction Run 1

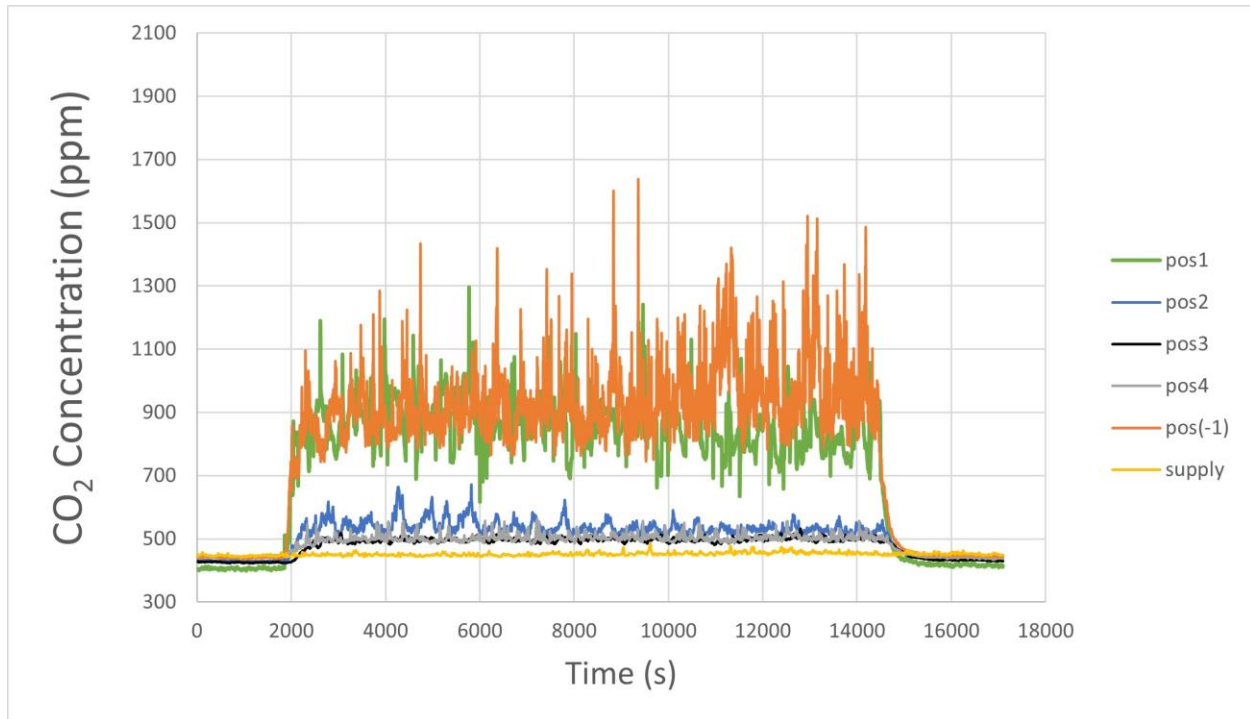


Figure 7.16: Row 7 Seat D Long Continuous, with T-Junction Run 2

The results for the Long Continuous Injections at Row 7 Seat D show a decrease in the amount of overall long-term response drift for the tests conducted with the T-Junction compared to those without. It cannot conclusively be stated that the T-Junction was solely responsible for these results due to the nature of variability between tests, however the only physical difference in variables between runs 1-2 and runs 3-4 was that of the T-Junction.

7.3.2: Row 7 Seat G

The use of the 5-way T was first tested at Row 7 Seat G due to the interesting divergence in results of the standard Continuous Injection at the location in comparison to their Row 7 Seat D counterparts, for the reasons described earlier in 7.3: Long Continuous Injection.

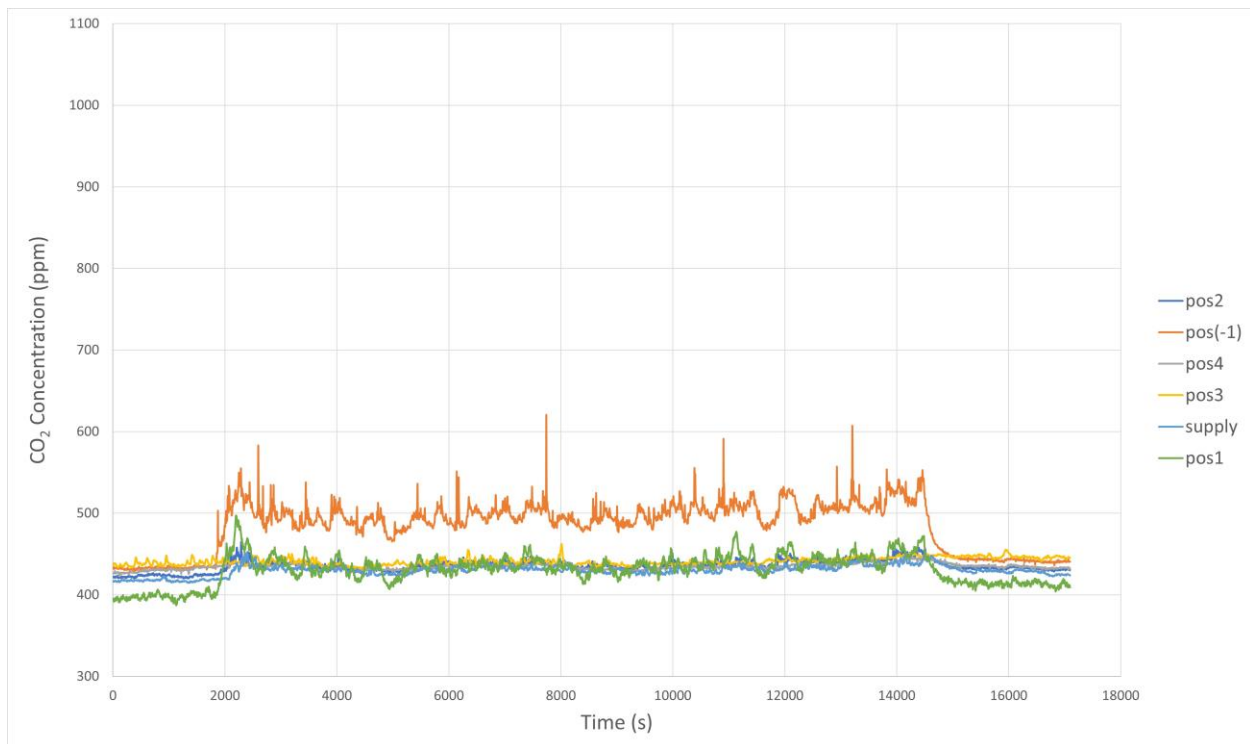


Figure 7.17: Row 7 Seat G Long Continuous, no T-Junction, Run 1

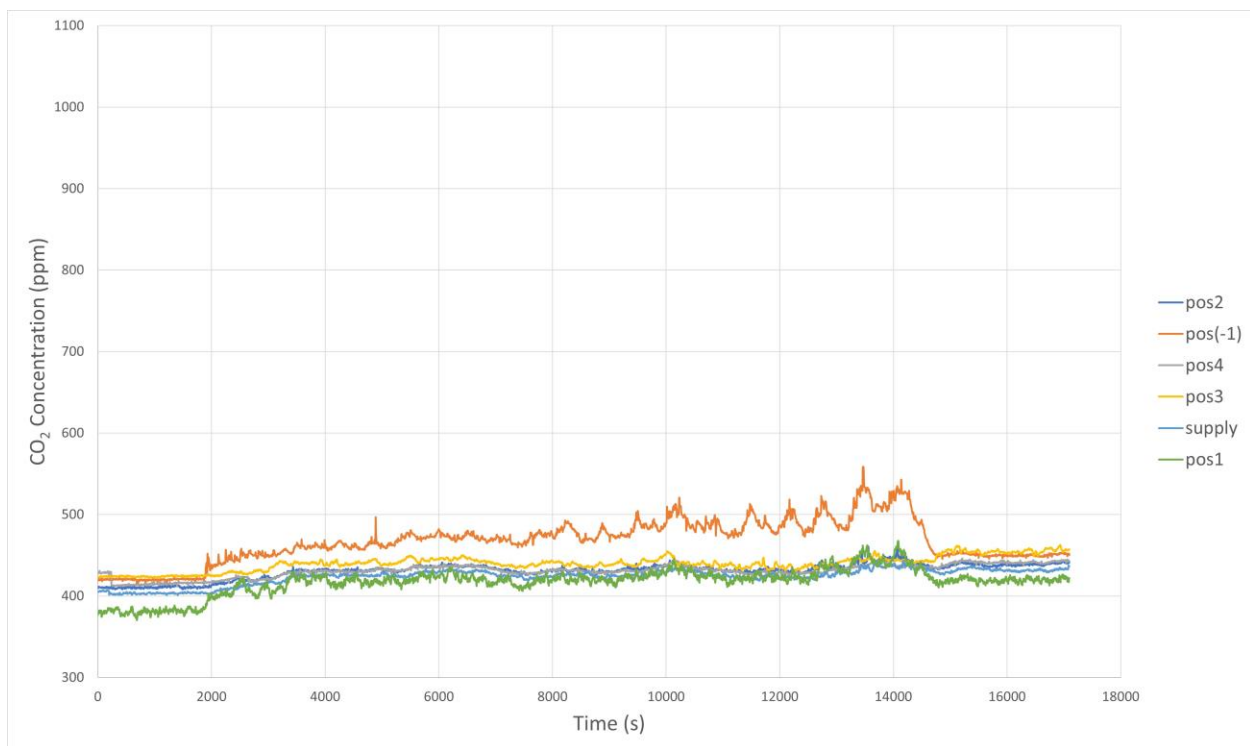


Figure 7.18: Row 7 Seat G Long Continuous, no T-Junction, Run 2

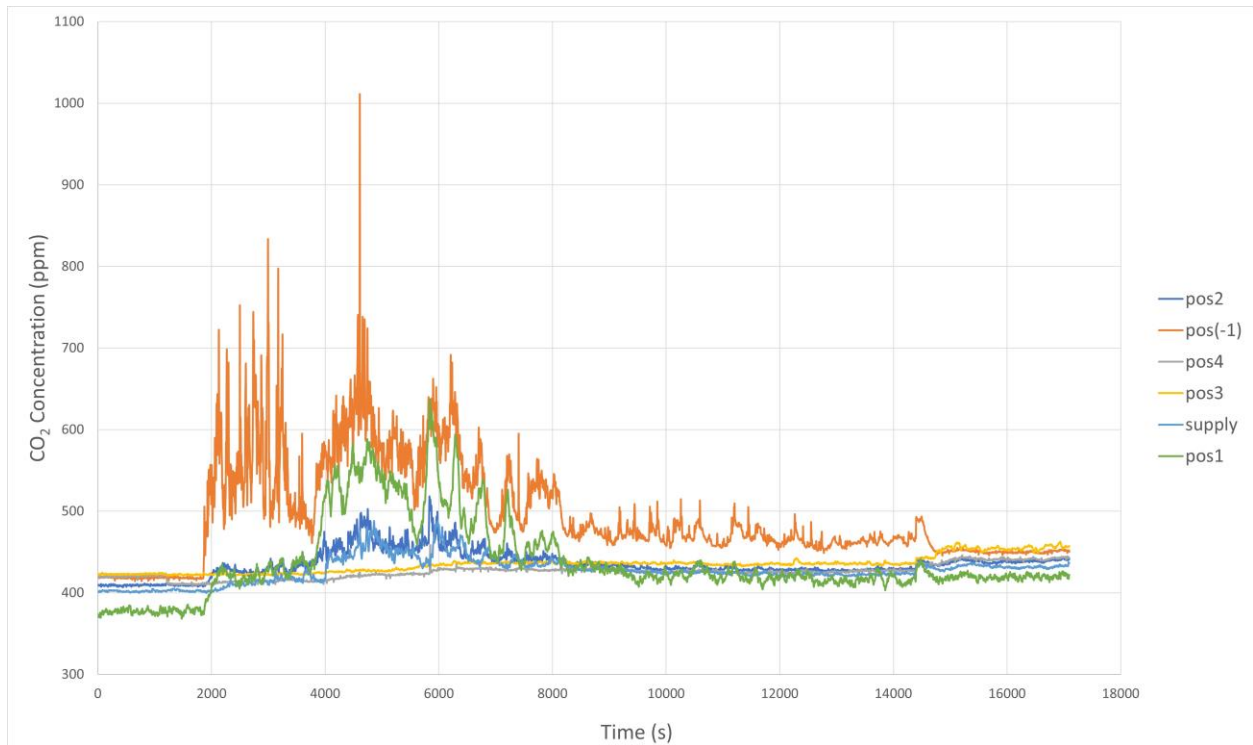


Figure 7.19: Row 7 Seat G Long Continuous, with T-Junction, Run 1

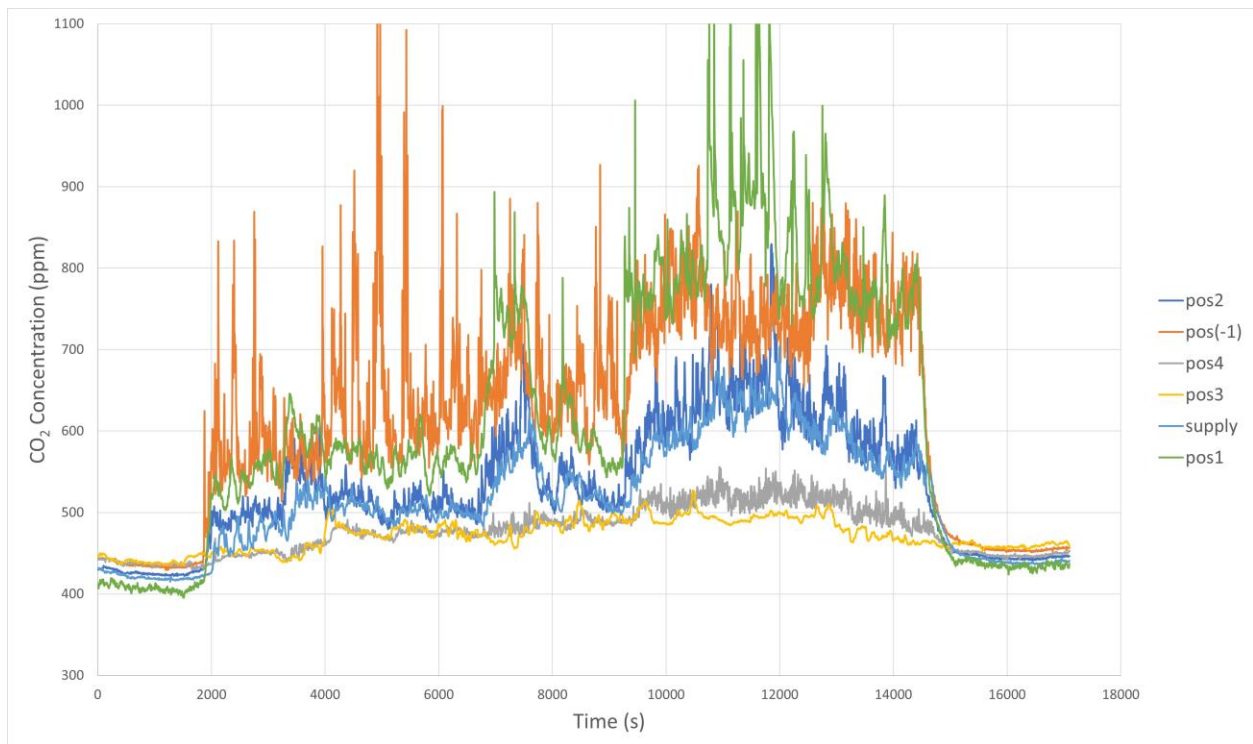


Figure 7.20: Row 7 Seat G Long Continuous, with T-Junction, Run 2

The effect of the T-Junction at Row 7 Seat G, based on these results, seems to be much greater than its effects at Row 7 Seat D. While there is significant drift long-term even with the T attached, the response (ppm values) is much higher overall. This is still true for Figure 7.19, which shows a reversion to the low response values after a ~100 minutes (6000 seconds) period during the injection phase. This could simply be due to the high variability between tests, which has been demonstrated for all injection types at both cabin locations.

7.4: Discussion

When taken together, the results of the 1-Minute, 3-Minutes and Continuous Injection offer some interesting insights. Chief among them is the chaotic nature of the local air currents surrounding the injection source and subsequent dispersion of tracer gas. There is a tremendous amount of variation between tests (for all three injection types); the results are unpredictable, and subject to drift mid-test. These drifts are hypothesized to be largely due to the local air currents around the injection source and around the sampling ports. The direction and speed of the current at one port can be radically different than that of another, let alone the injection source, which can explain the variation between tests. This hypothesis also accounts for the drifts seen primarily in the continuous injections. The currents themselves can change mid-tests (see chapter 8), affecting the dispersion of tracer gas, and how each location records the carbon dioxide concentration. This makes multiple tests per injection types necessary to capture a more accurate average representation of the behavior at that location. If only a single test is taken, or even a few tests (i.e., in triplicate), there is potential for the results to be non-representative if the currents change. These results show that the dispersion of a single airborne contaminant release can be very unpredictable for any location.

Another key takeaway is the difference between testing locations. The 1-Minute and 3-Minutes Puff Injection results are not too dissimilar per sensor position between the Row 7 Seat D and Row 7 Seat G positions, which can be seen in Figure 7.21, Figure 7.22 and Figure 7.23.

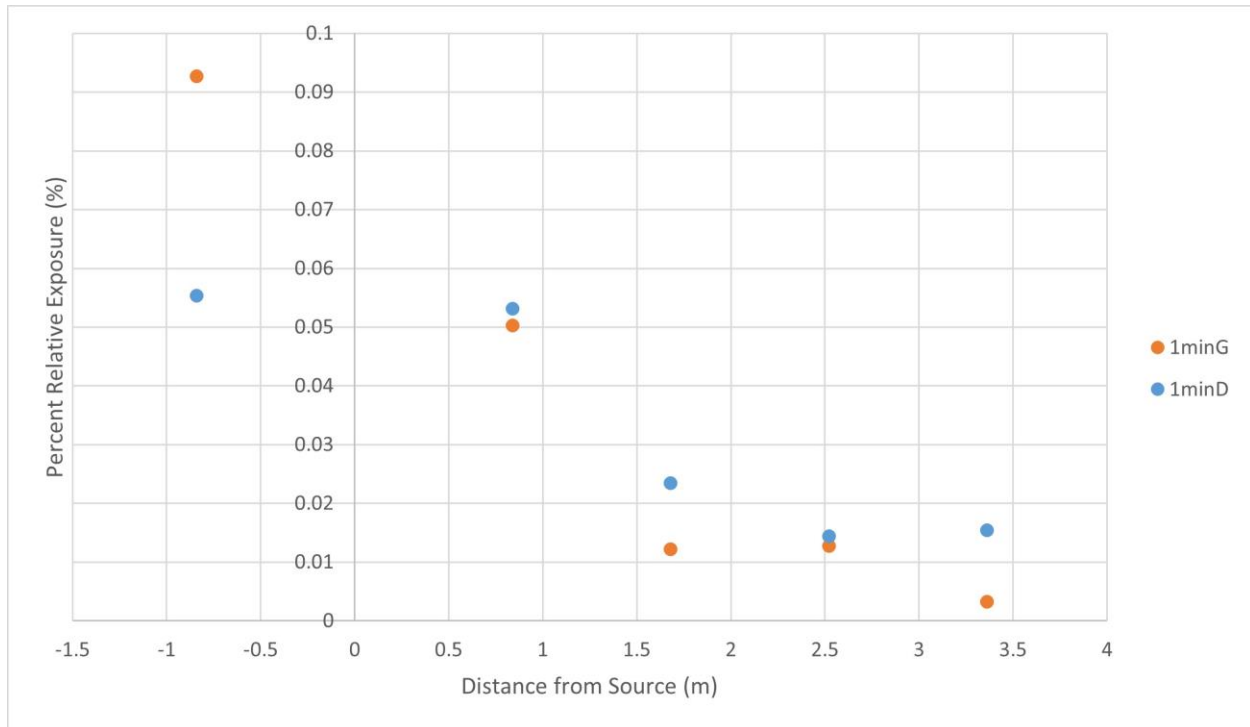


Figure 7.21: 1-Minute Puff Injection Combined Testing Location Means

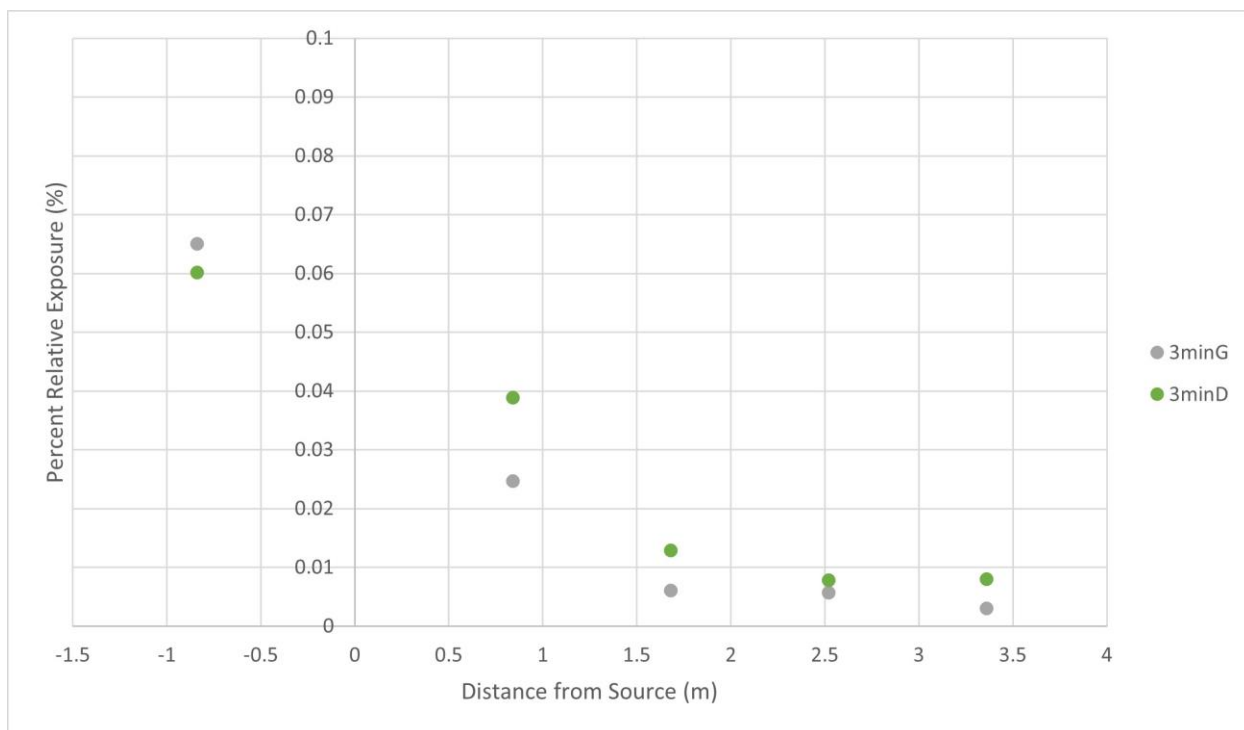


Figure 7.22: 3-Minutes Puff Injection Combined Testing Location Means

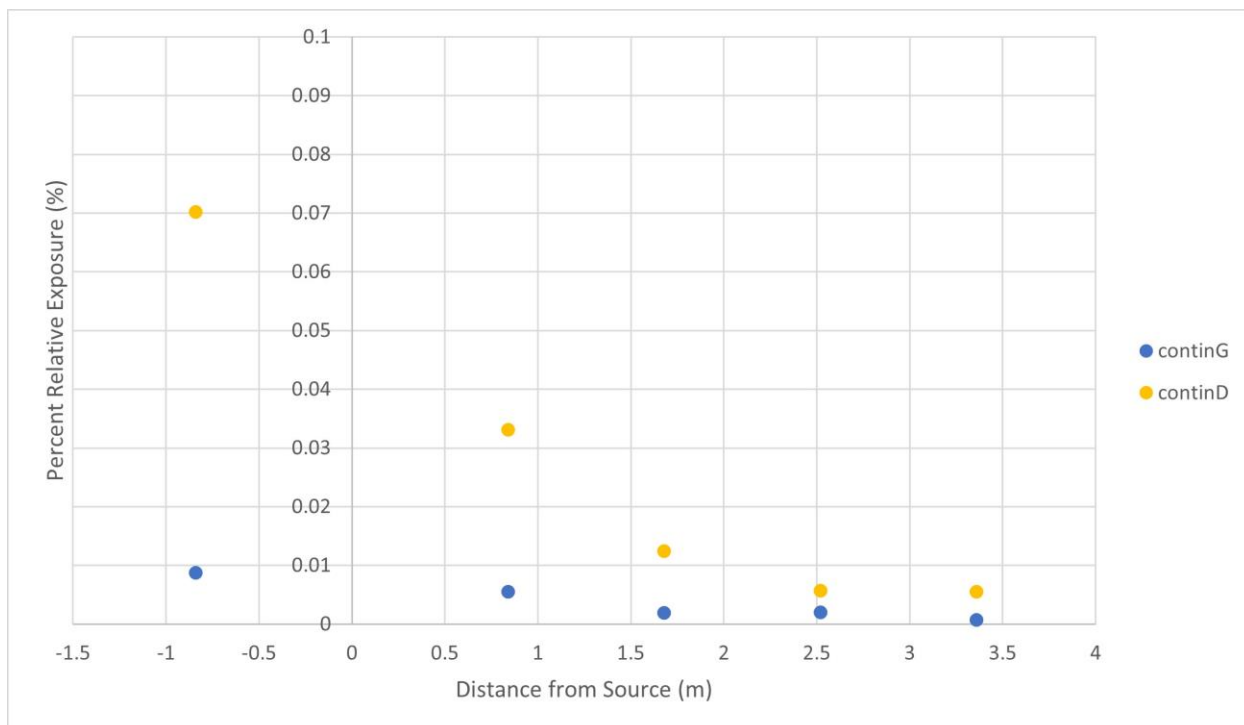


Figure 7.23: Continuous Injection Combined Testing Location Means

The only difference in variables between testing locations was the location itself, thus lending the question of how the location affects dispersion. One potential explanation is a wall-effect of the cabin at tests for Row 7 Seat G, i.e., the diffuser air current attaches to the wall and flows down it. As the injection source is very near the wall, the continuously injected air becomes entrained by the air current attached to the wall. The injection plume does not have the momentum to overcome the momentum of the wall air current.

7.5: Recommendations for Future Research

This current study has shown that there can be extreme variation between tests of the same injection types, notably in the continuous injection regime. In theory, the puff injections should have less variability, as there isn't a continuously replenished local gas supply (only 1/3 minutes of injection), thus there is much less mixing over the puff injection timeframe compared to the continuous timeframe. Less mixing leads to less variation. This variation, which is most often reflected in behavioral shifts in carbon dioxide response, should be further investigated. What is causing this variation, and are there any patterns to this variation?

There is evidence in the response graphs for the presence of what has been coined as “metastable flow structures”, which were hinted at back in 6.2.1.1: Continuous Injection and 6.2.2.1: Continuous Injection, and in the results of (Mahmoud, 2021) in 2.3: Foundations. There is evidence for them in the puff injection types also, but the behavior is best seen in the continuous injection regime, where the response patterns change dramatically. These response patterns shifting have a marked effect on the percent relative exposure calculations performed, best illustrated by the high degree of variance in the values for both the Row 7 Seat D and Row 7 Seat G Continuous Injection test results (see Figure 7.1, Figure 7.7). It is the physical source of these response shifts that remain unanswered. It should be researched further if there are indeed

these flow structures present, and if so, how much do they dictate the variation (responses) that is clearly seen between some tests? How do the flow pattern results of Shehadi, 2015 compare with the findings of this current study? These must be addressed in future research.

(Shehadi, 2015), through the use of smoke visualization, proposed flow patterns inside the cabin, as seen in Figure 7.24, based on local smoke visualization results, as seen in Figure 7.25.

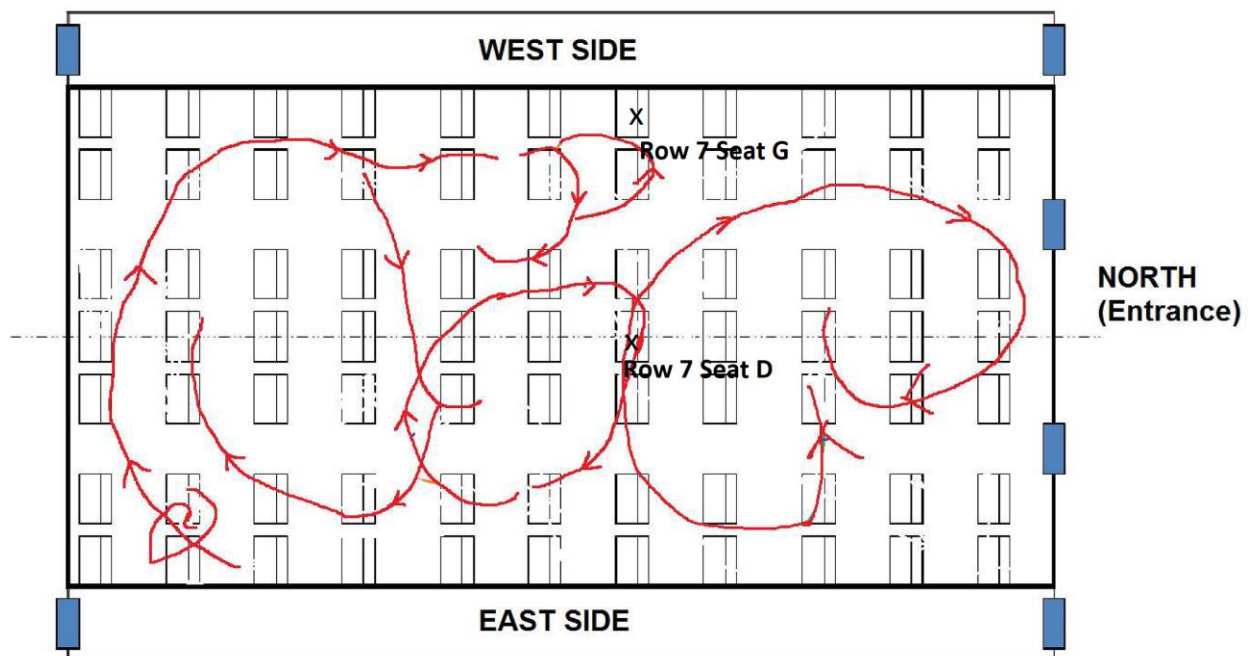


Figure 7.24: Proposed Flow Patterns Inside the Cabin Based on Smoke Visualization Tests (Shehadi, 2015)

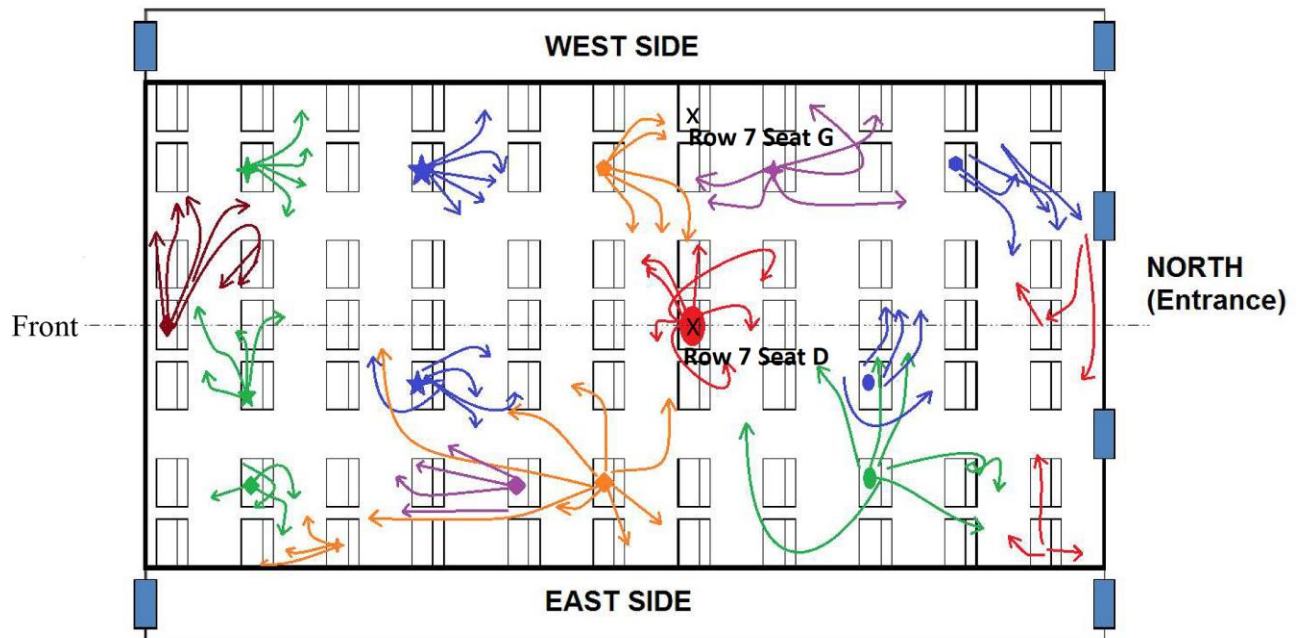


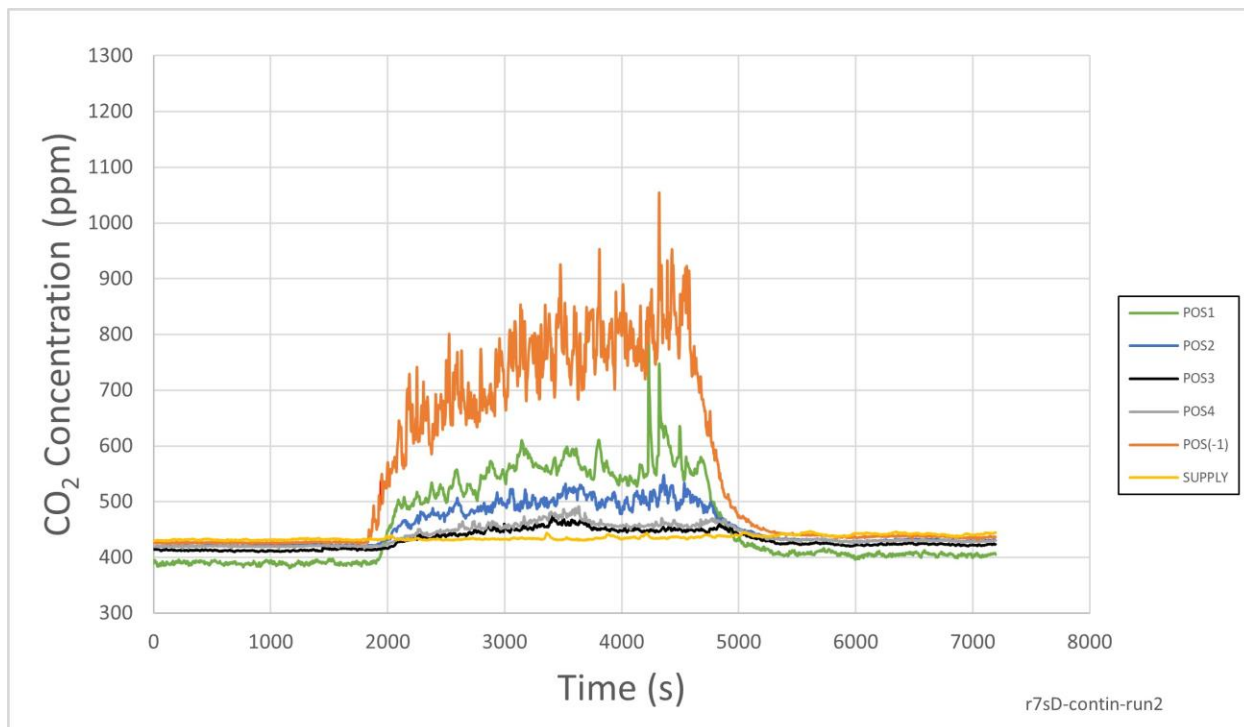
Figure 7.25: Local Smoke Visualization Results (Shehadi, 2015)

One question for future research would be to validate the flow patterns seen in Shehadi, 2015, by increasing the number of smoke tests. As was stated previously, due to the variation between tests seen in this current study, more than a handful of tests is required to fully capture the behavior of the system. In doing more tests, would the smoke visualization confirm the presence of metastable flow structures, and if so, provide any detail as to their duration and frequency of shifts?

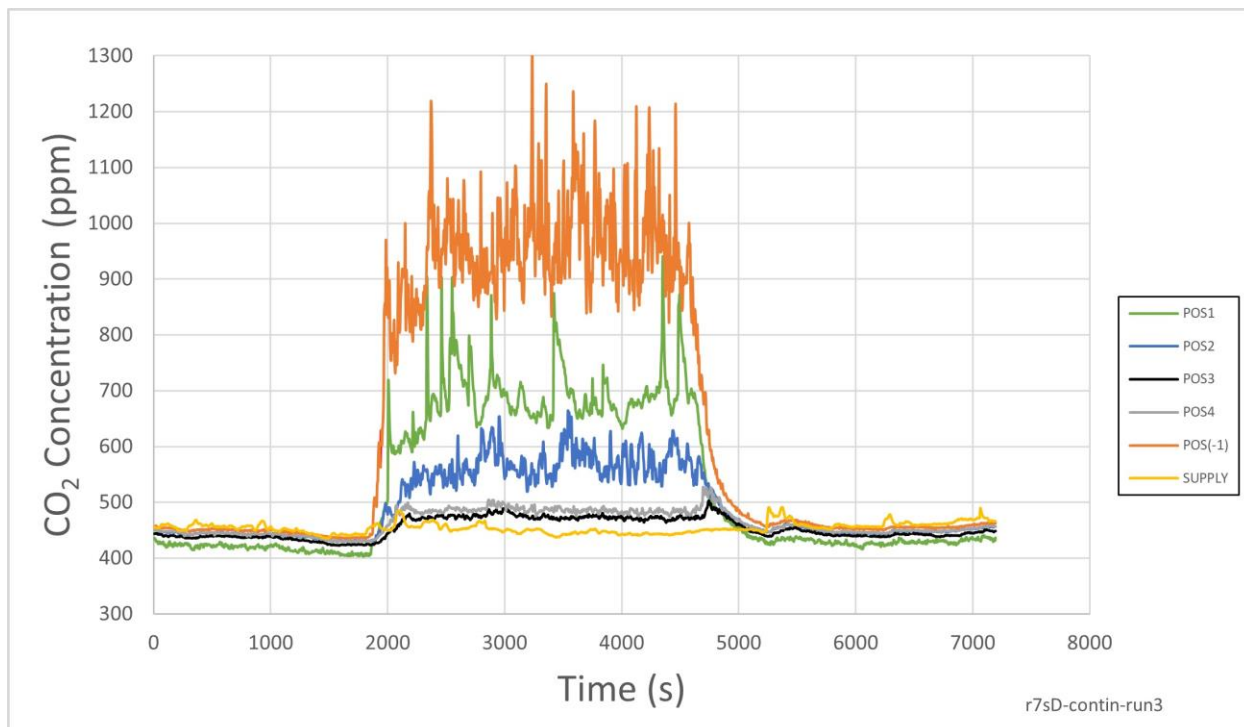
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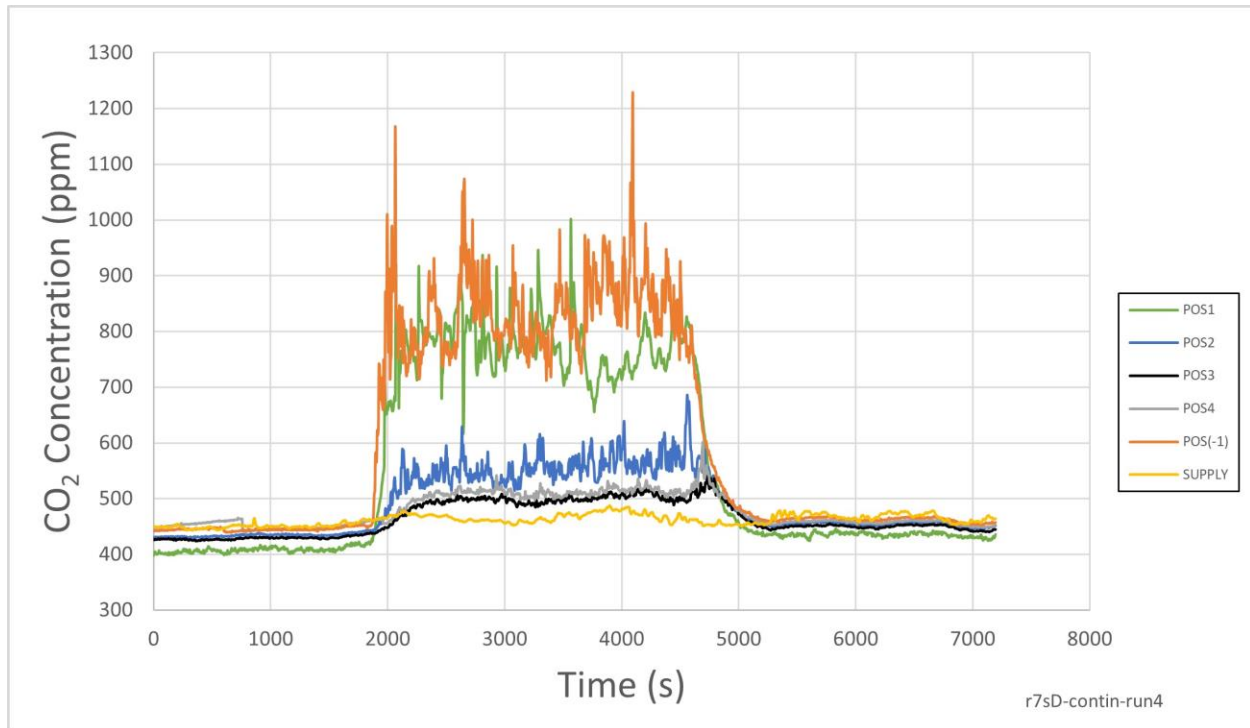
Appendix A - Row 7 Seat D – Continuous Injection Responses



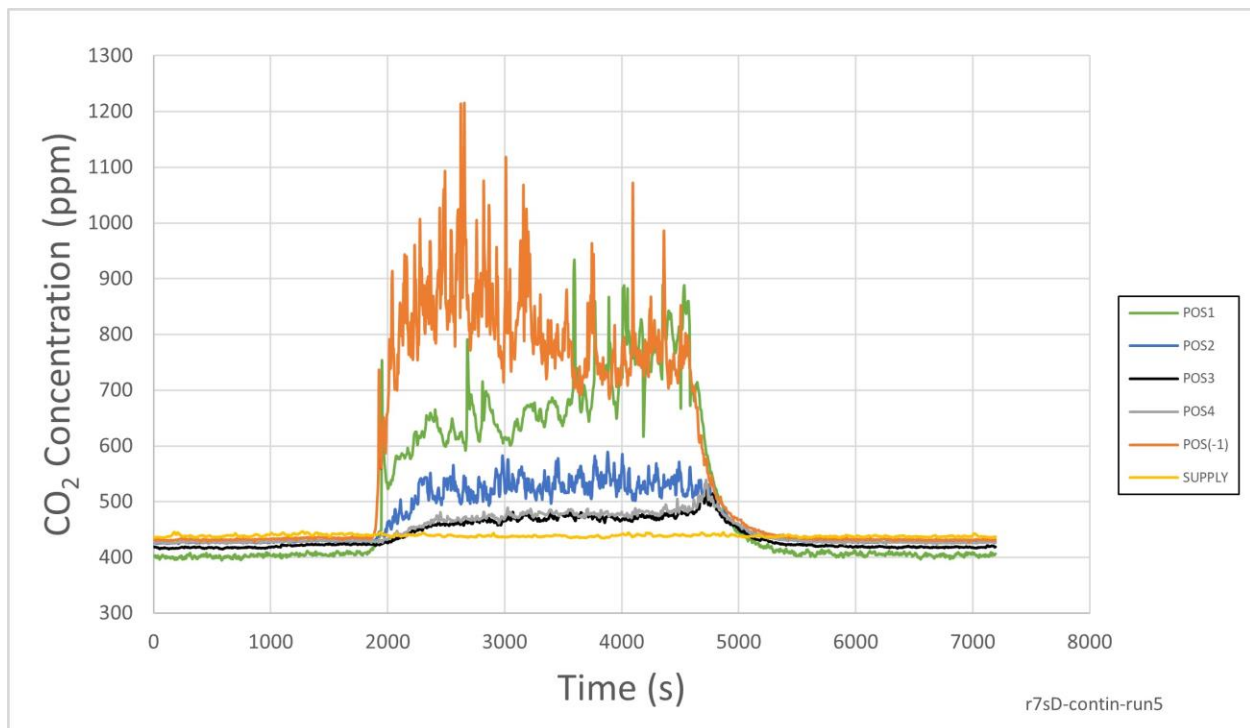
Appendix A A.1: Row 7 Seat D – Continuous – Run1



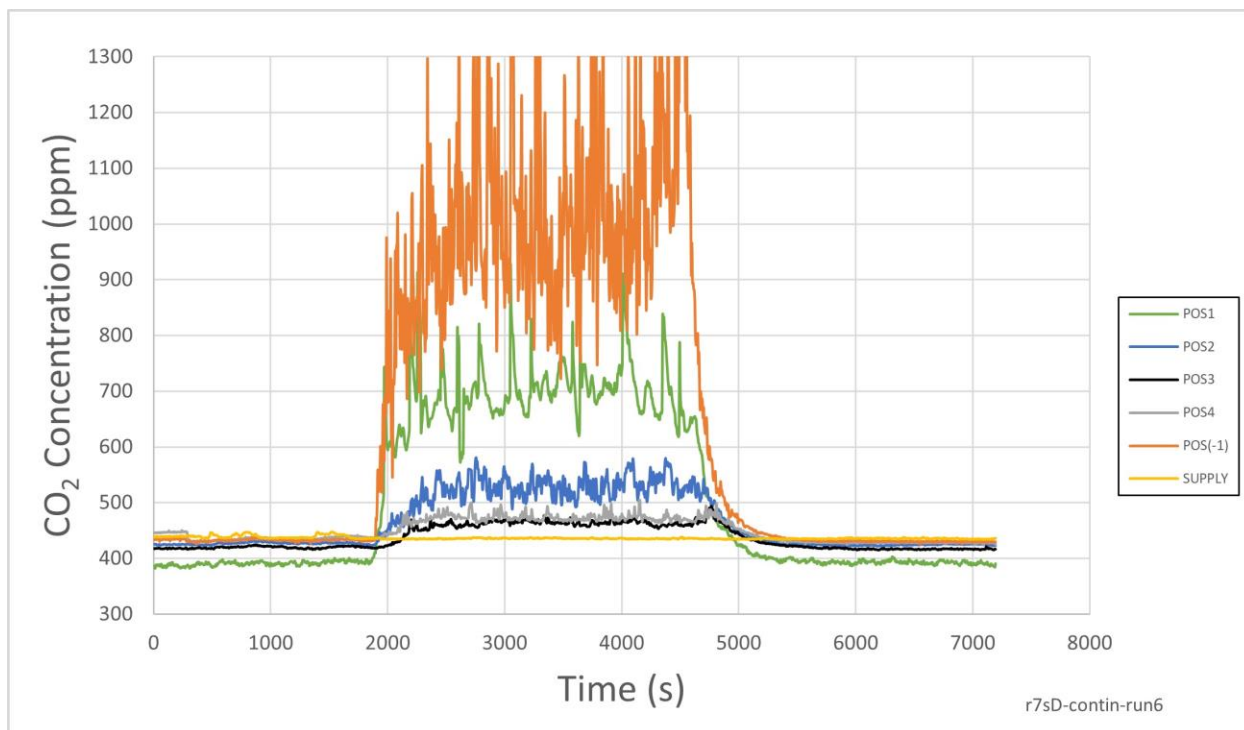
Appendix A A.2: Row 7 Seat D – Continuous – Run2



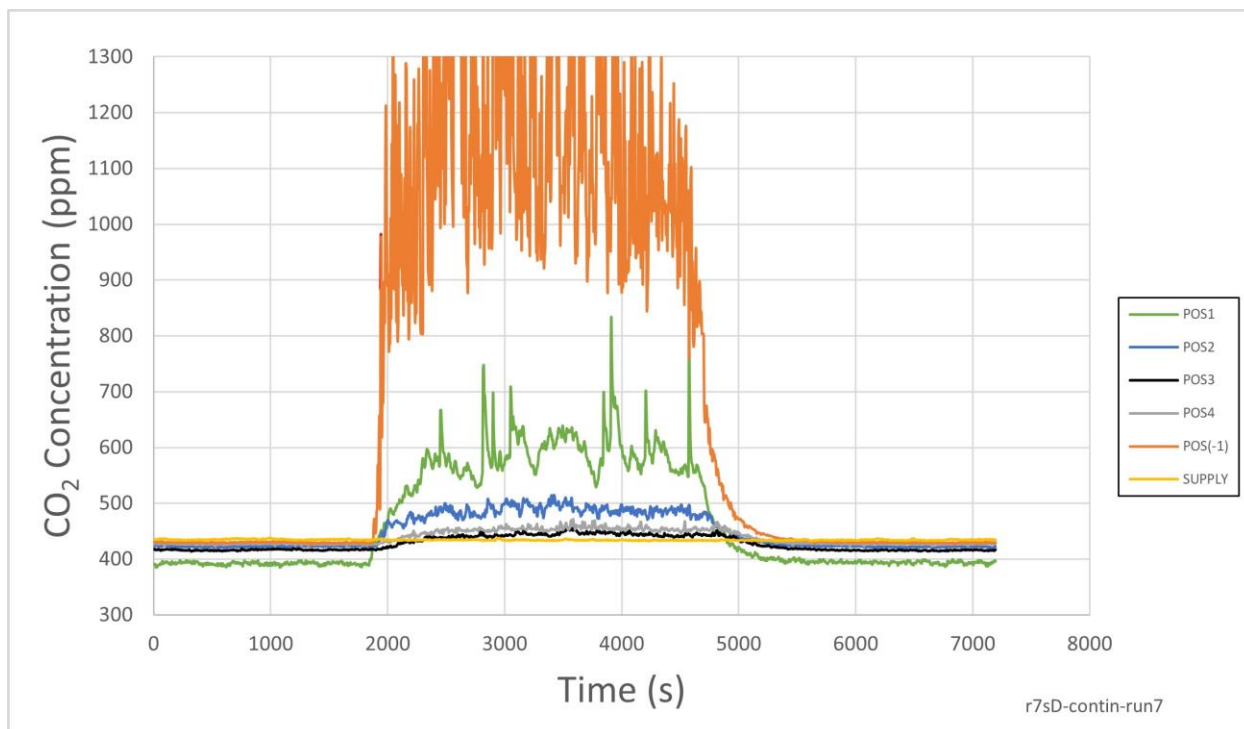
Appendix A A.3: Row 7 Seat D – Continuous – Run3



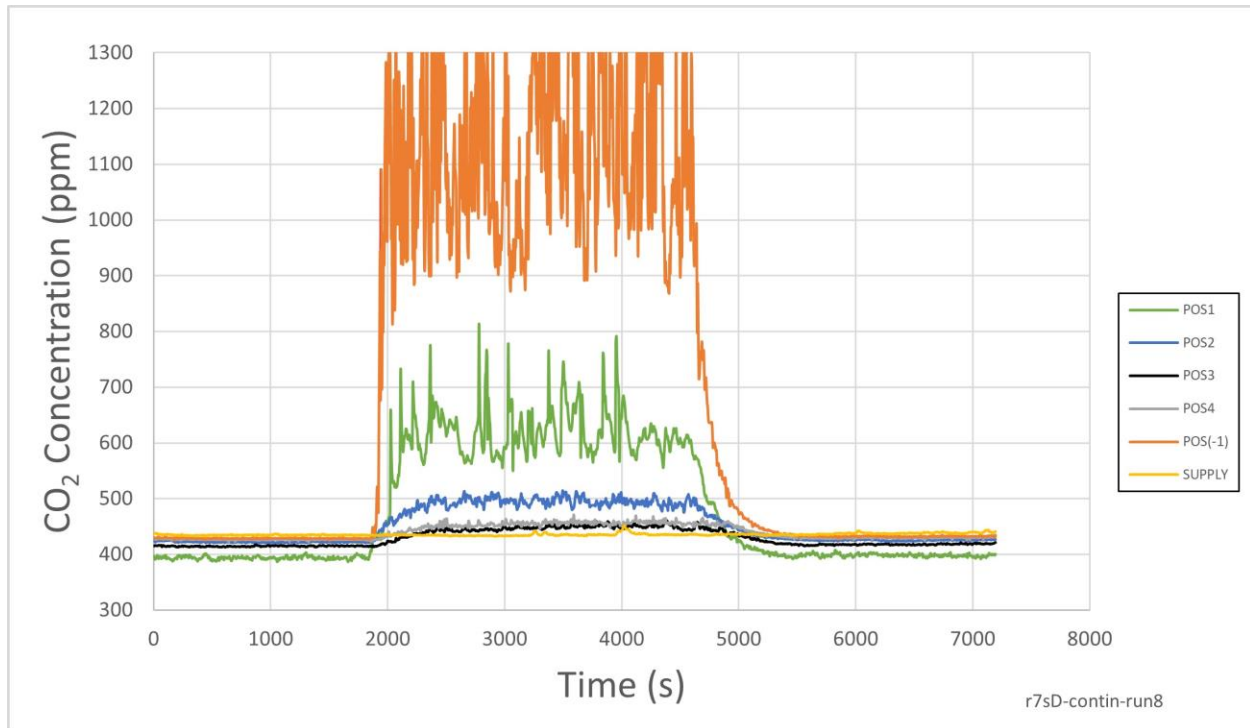
Appendix A A.4: Row 7 Seat D – Continuous – Run4



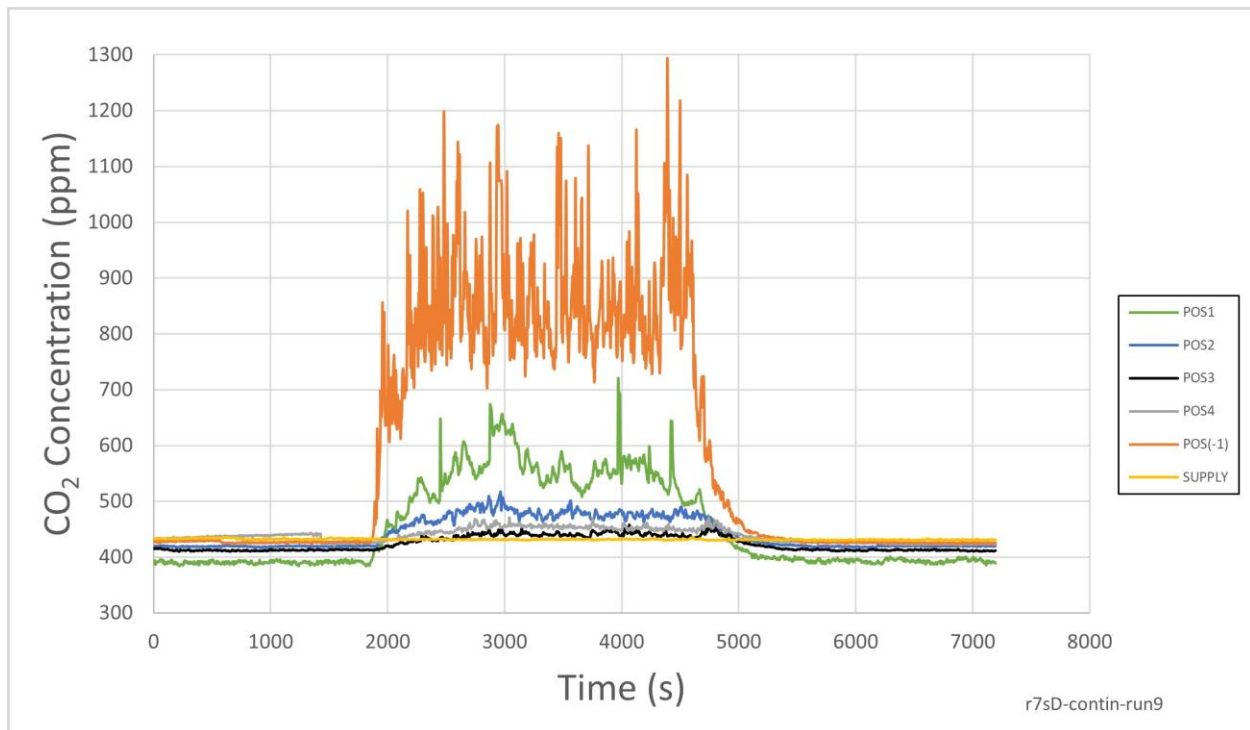
Appendix A A.5: Row 7 Seat D – Continuous – Run5



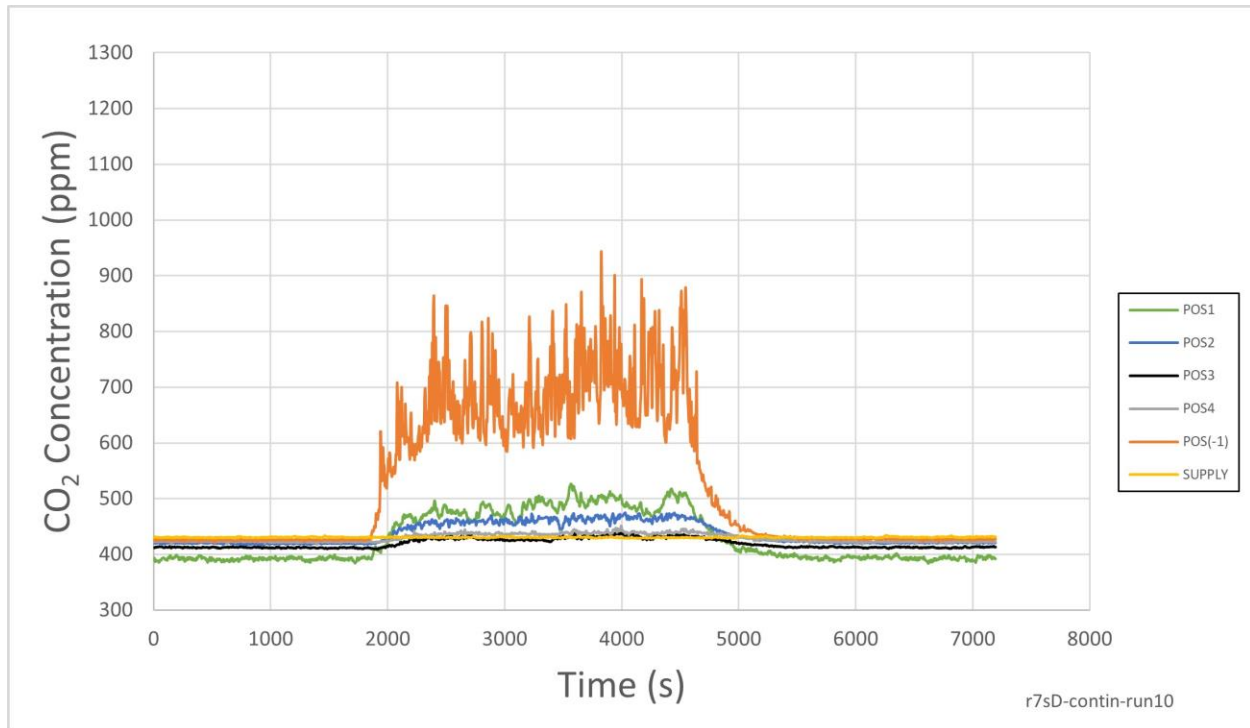
Appendix A A.6: Row 7 Seat D – Continuous – Run6



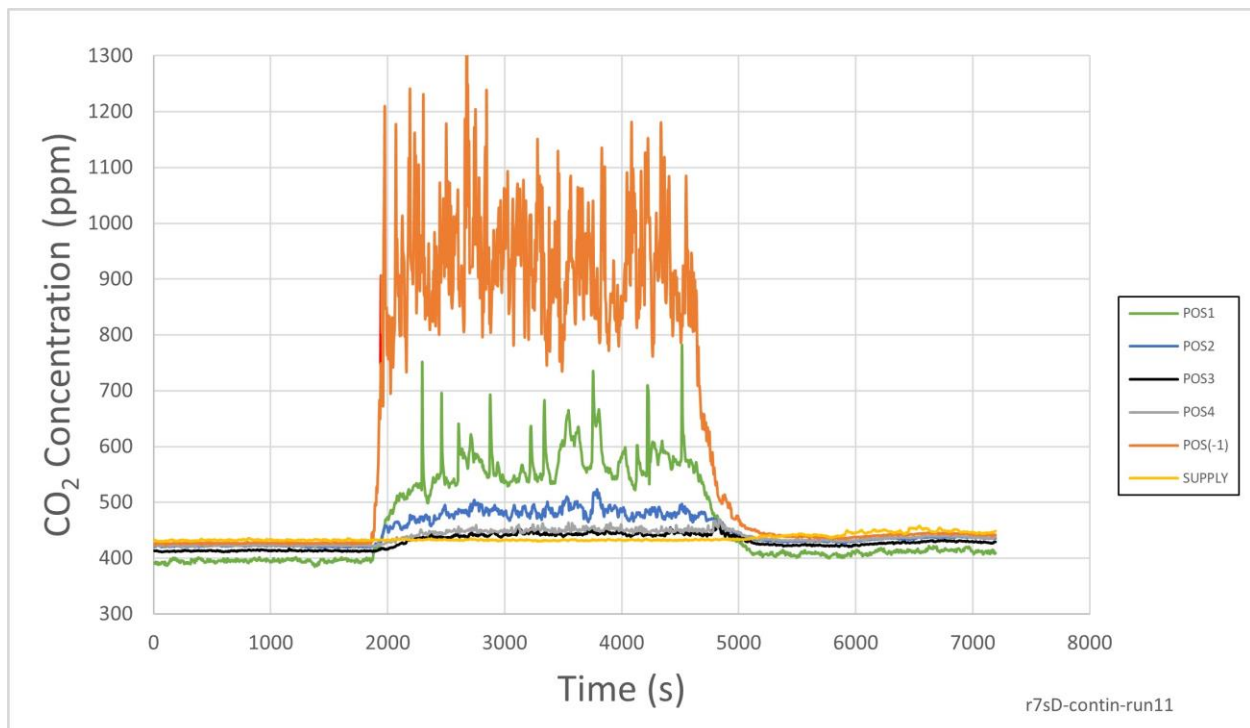
Appendix A A.7: Row 7 Seat D – Continuous – Run7



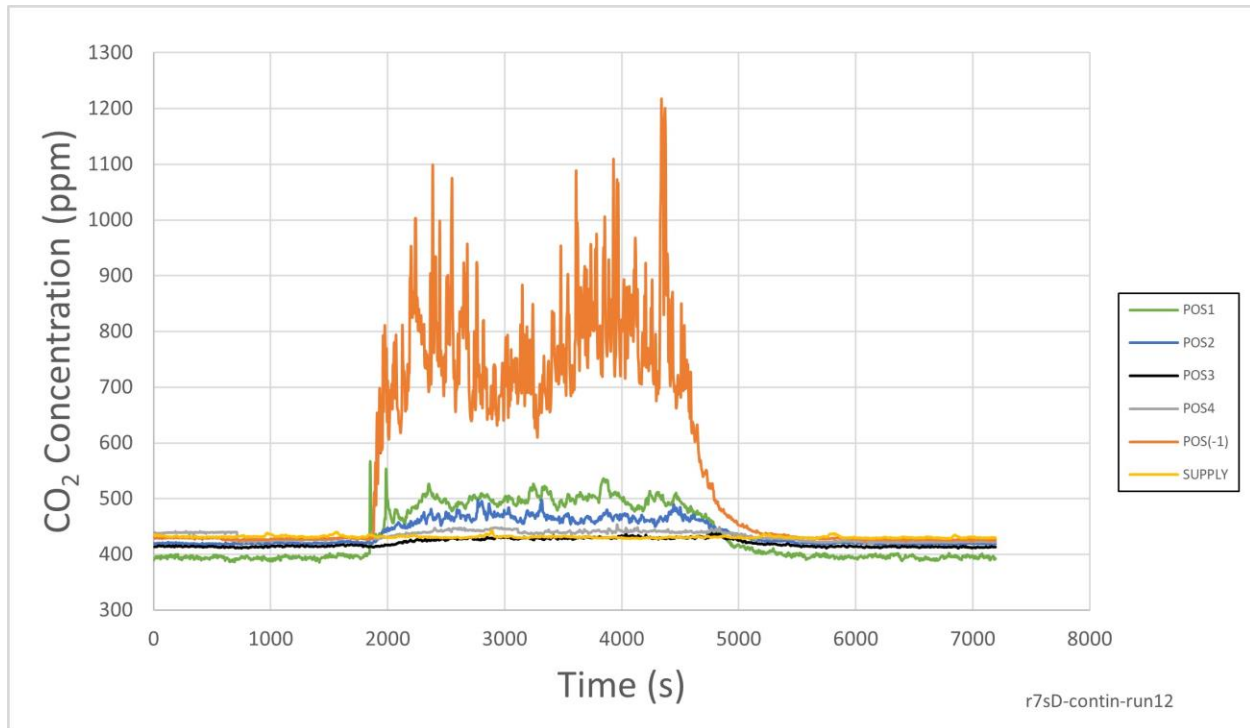
Appendix A A.8: Row 7 Seat D – Continuous – Run8



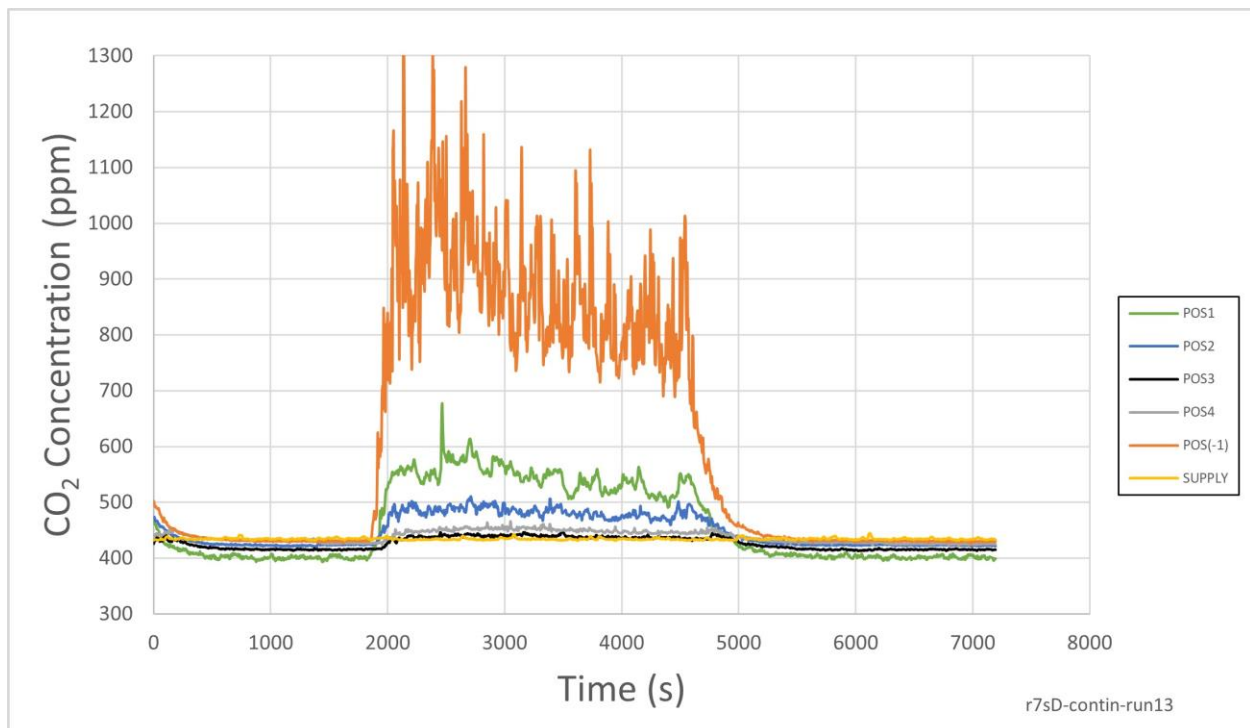
Appendix A A.9: Row 7 Seat D – Continuous – Run9



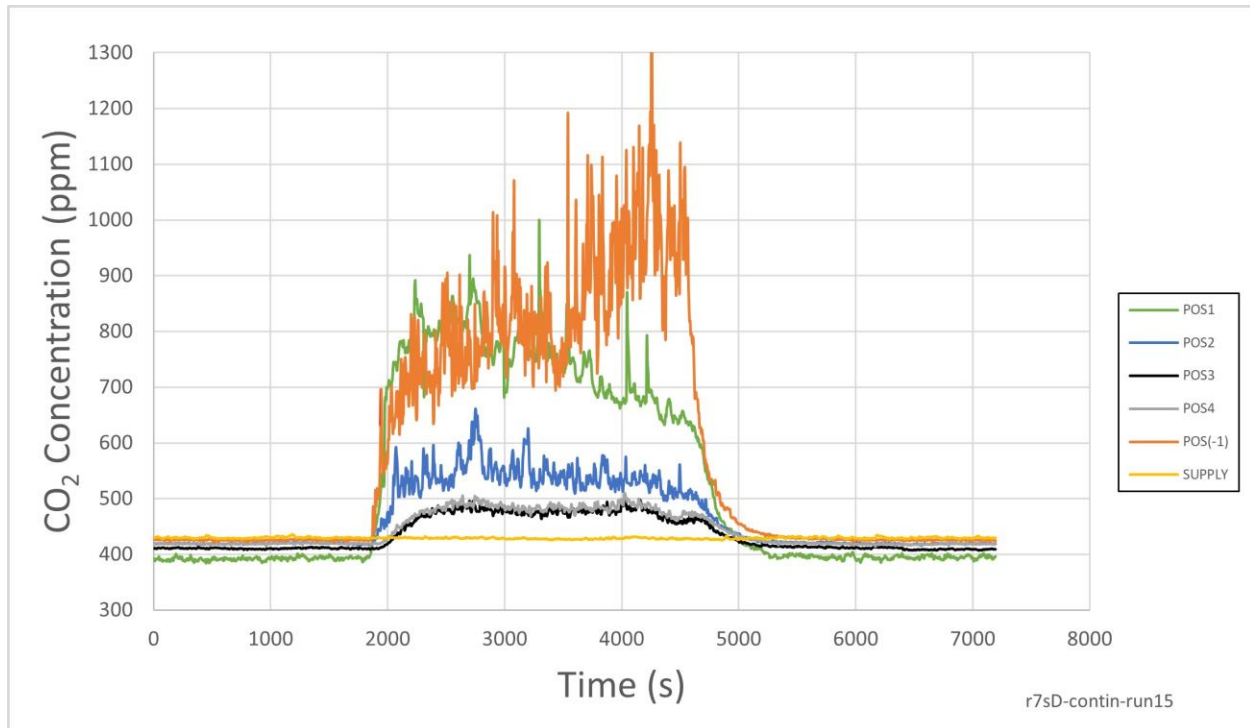
Appendix A A.10: Row 7 Seat D – Continuous – Run10



Appendix A A.11: Row 7 Seat D – Continuous – Run11

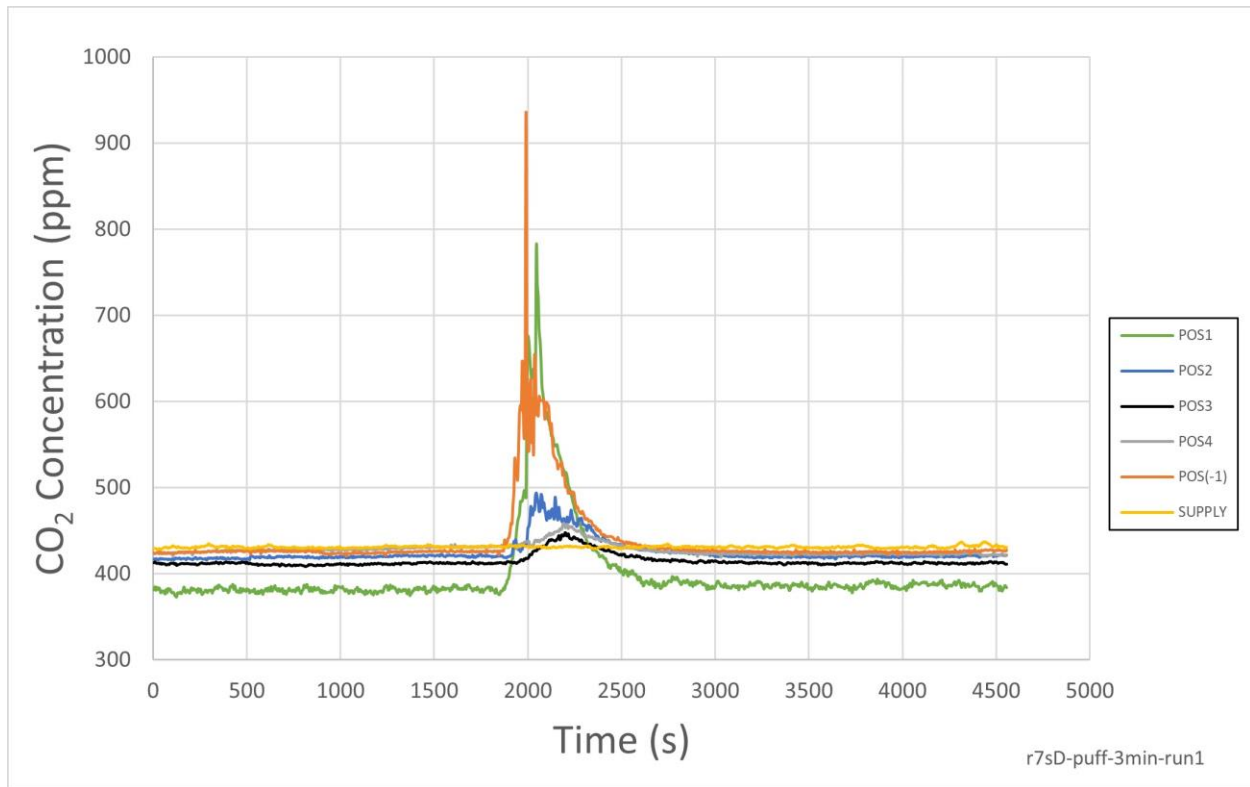


Appendix A A.12: Row 7 Seat D – Continuous – Run12

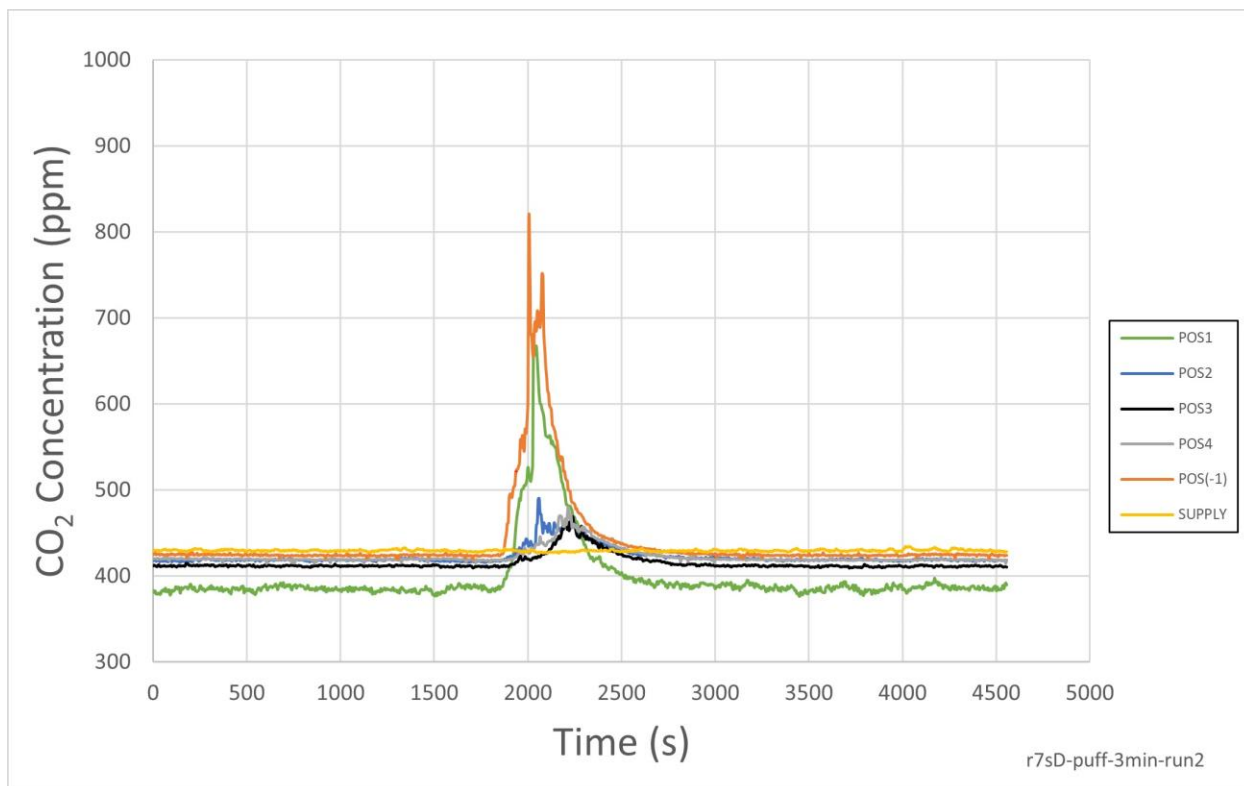


Appendix A A.13: Row 7 Seat D – Continuous – Run13

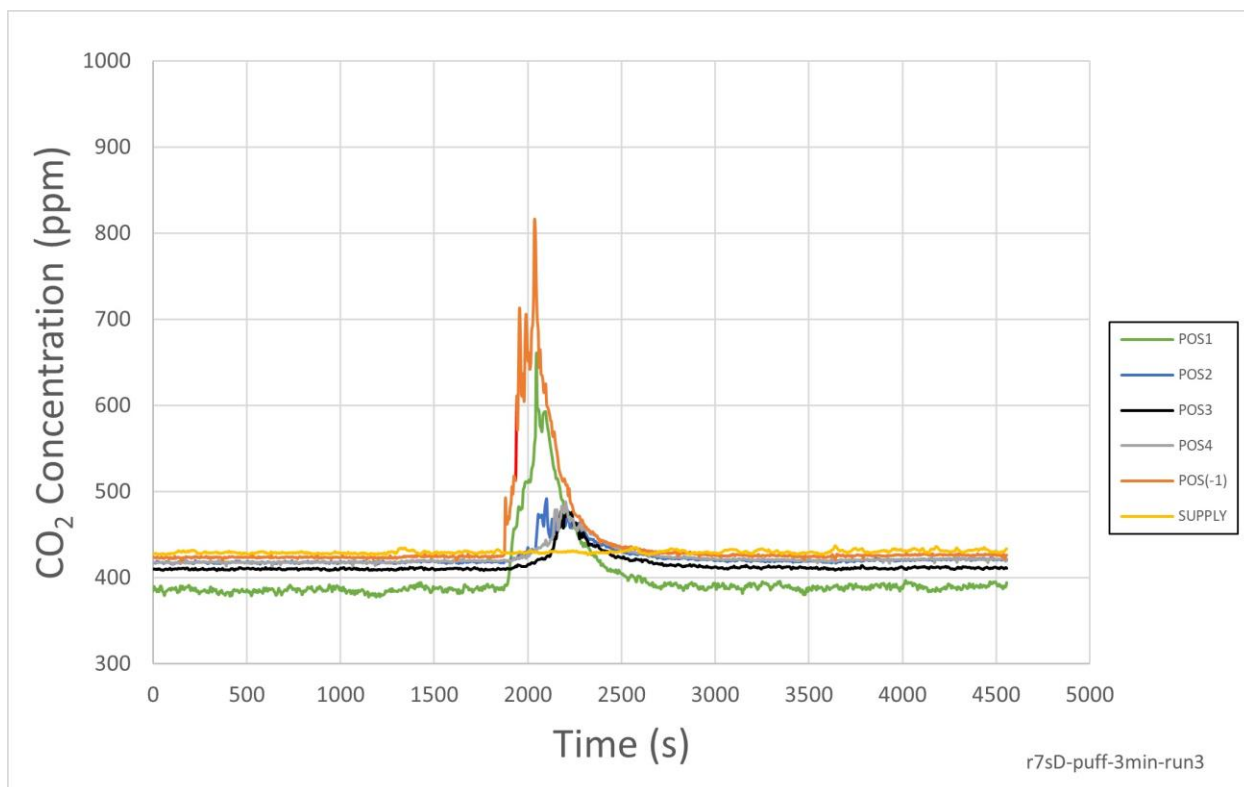
Appendix B - Row 7 Seat D – Puff Injection Responses



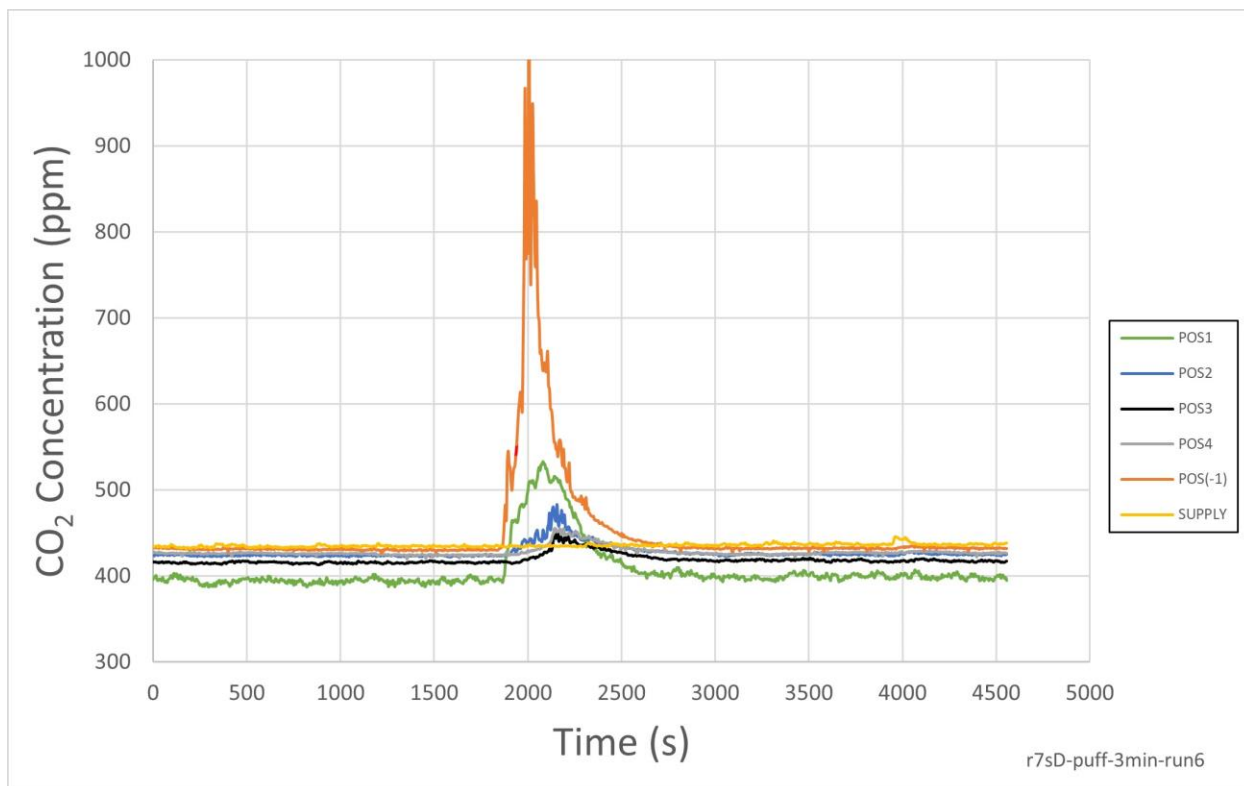
Appendix B B.1: Row 7 Seat D – 3-Minutes Puff – Run 1



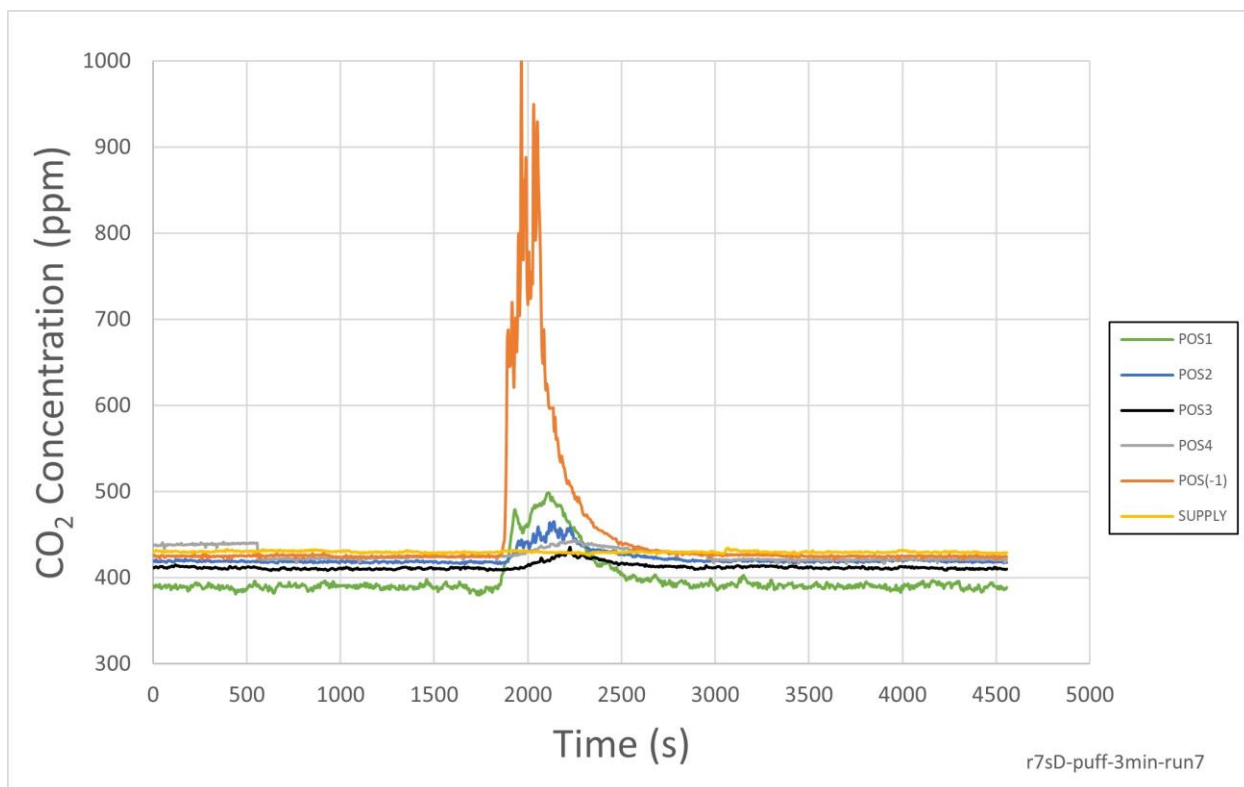
Appendix B B.2: Row 7 Seat D – 3-Minutes Puff – Run 2



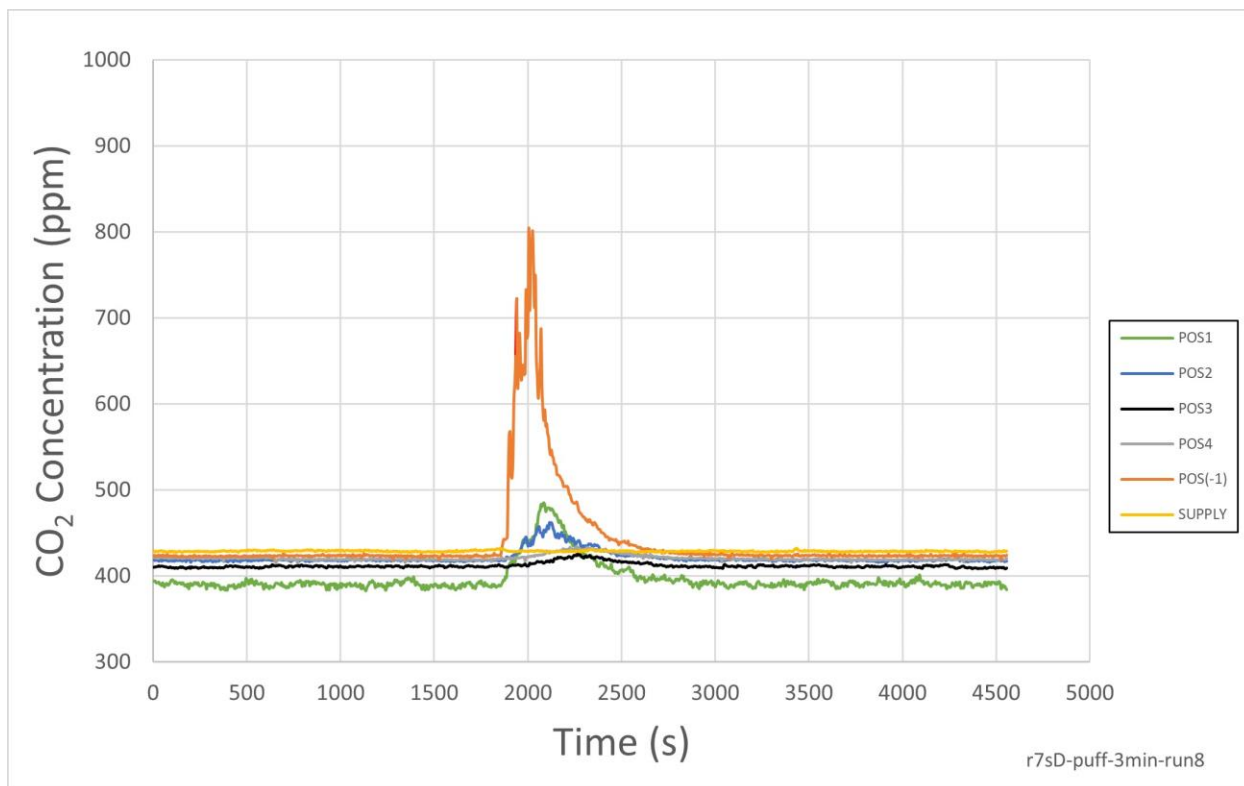
Appendix B B.3: Row 7 Seat D – 3-Minutes Puff – Run 3



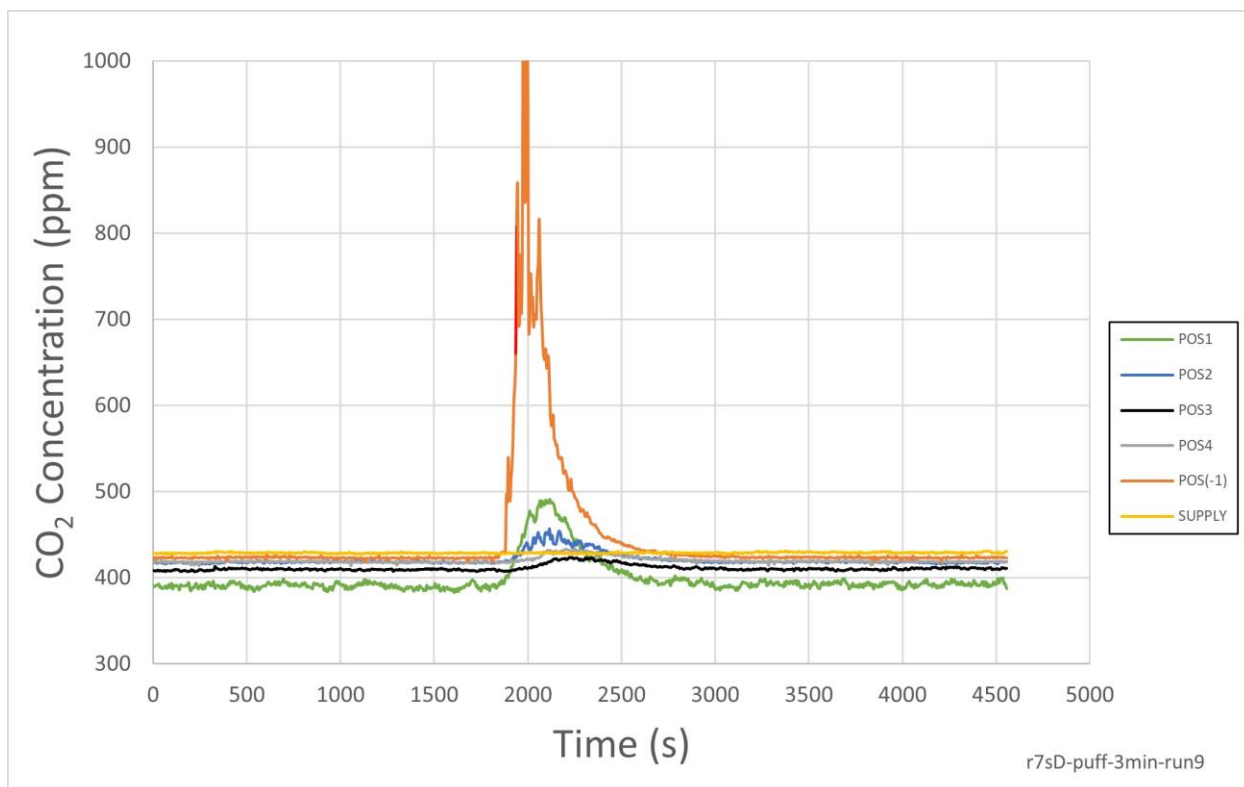
Appendix B B.4: Row 7 Seat D – 3-Minutes Puff – Run 4



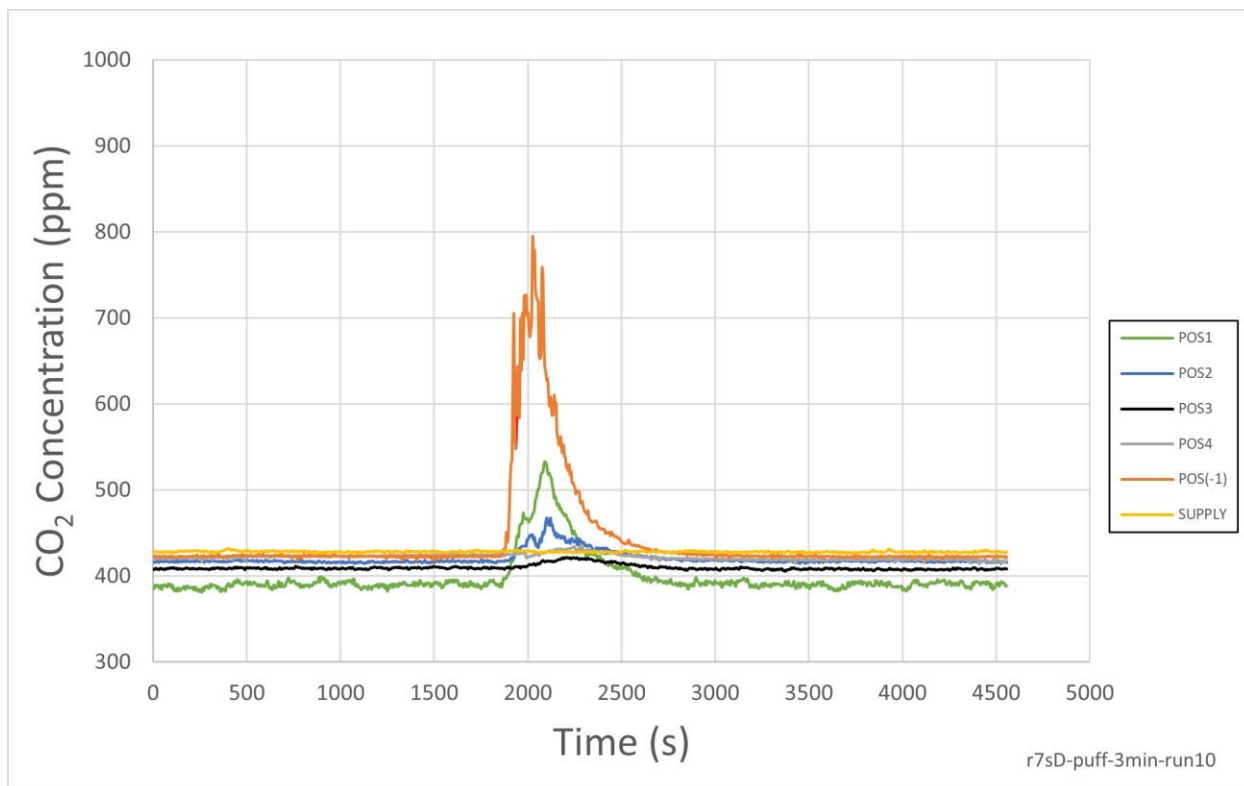
Appendix B B.5: Row 7 Seat D – 3-Minutes Puff – Run 5



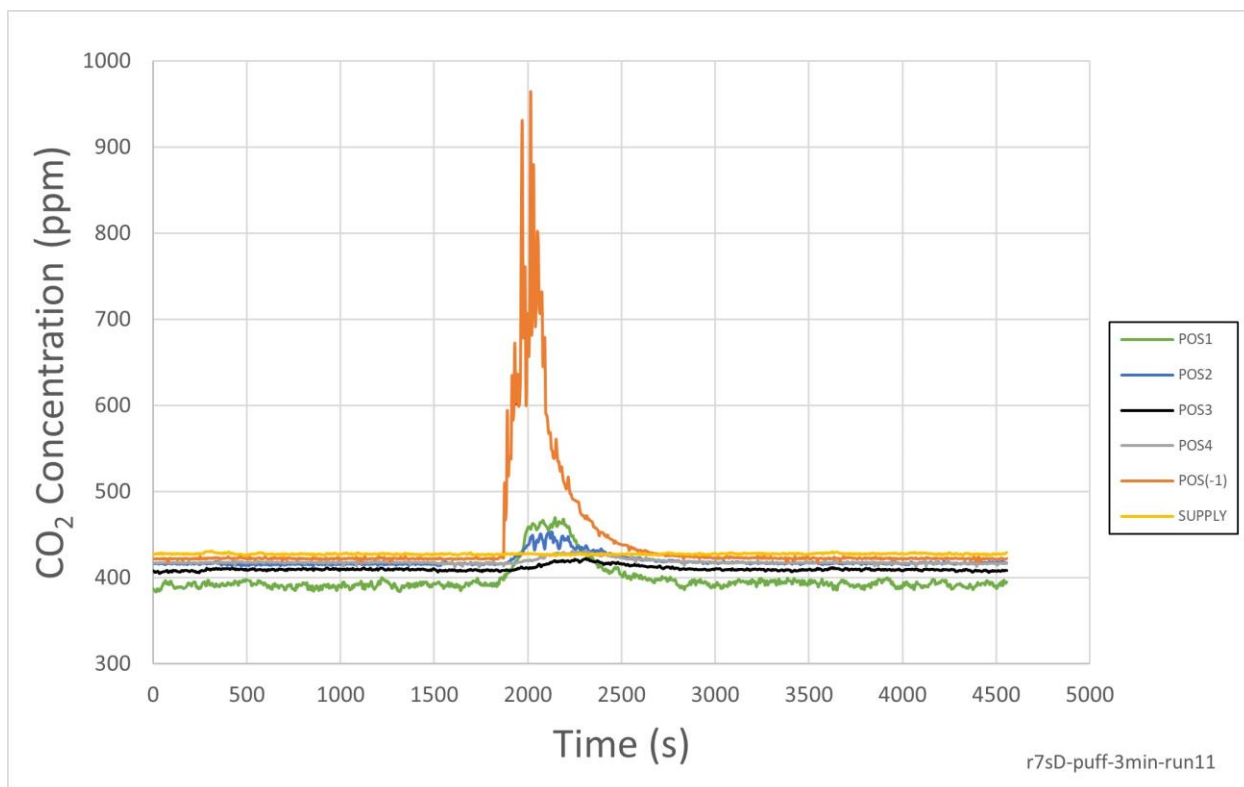
Appendix B B.6: Row 7 Seat D – 3-Minutes Puff – Run 6



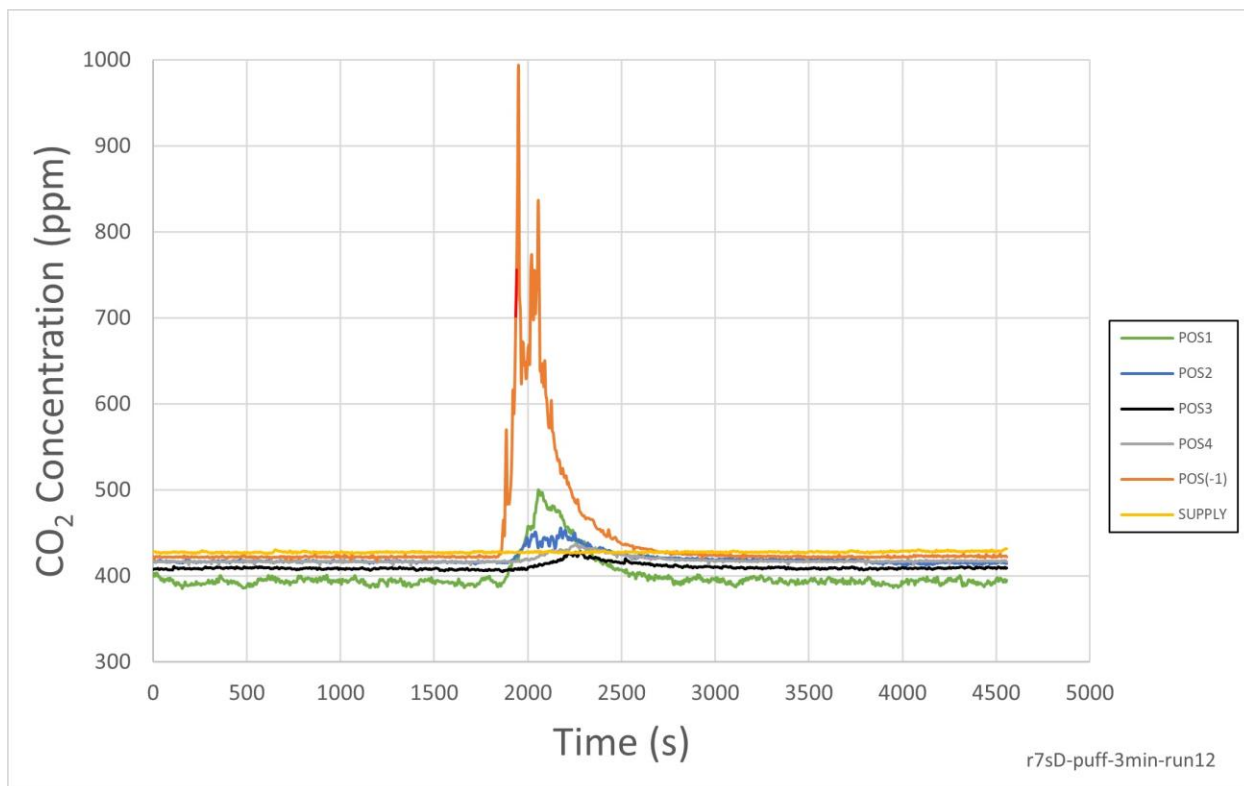
Appendix B B.7: Row 7 Seat D – 3-Minutes Puff – Run 7



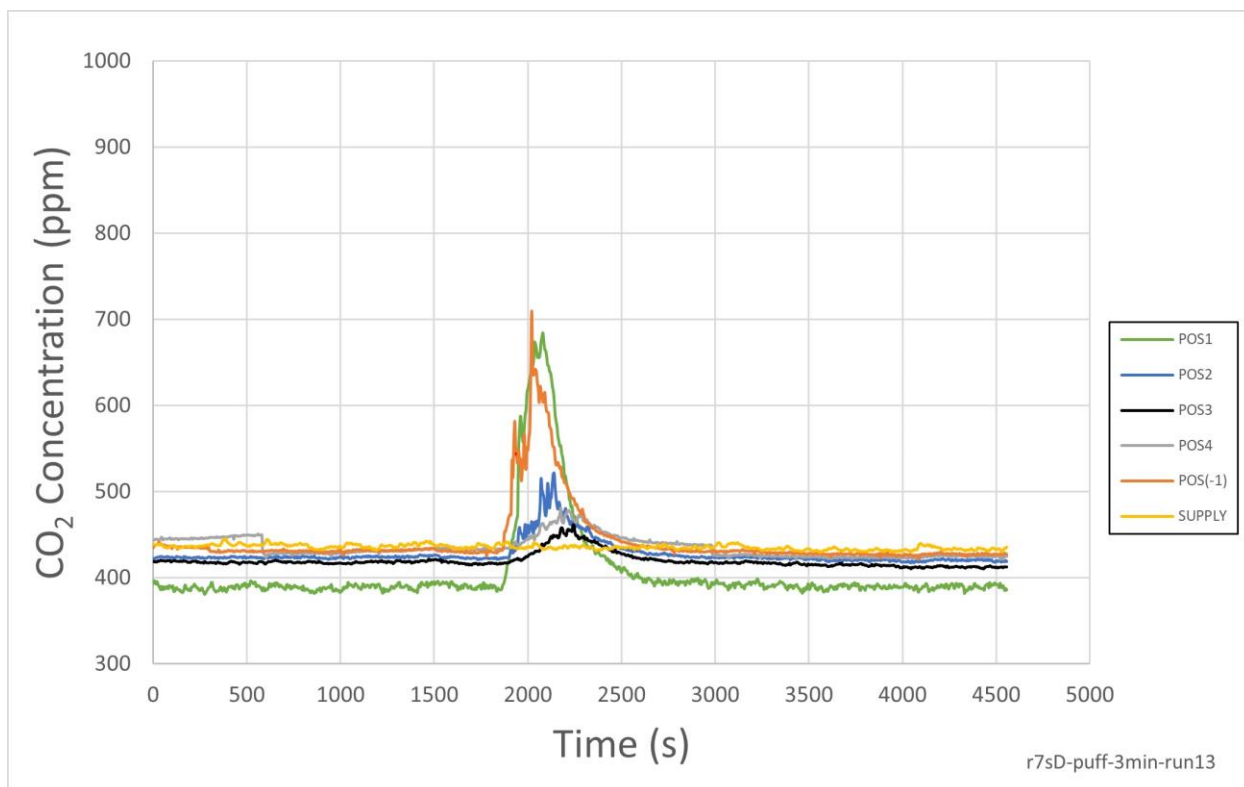
Appendix B B.8: Row 7 Seat D – 3-Minutes Puff – Run 8



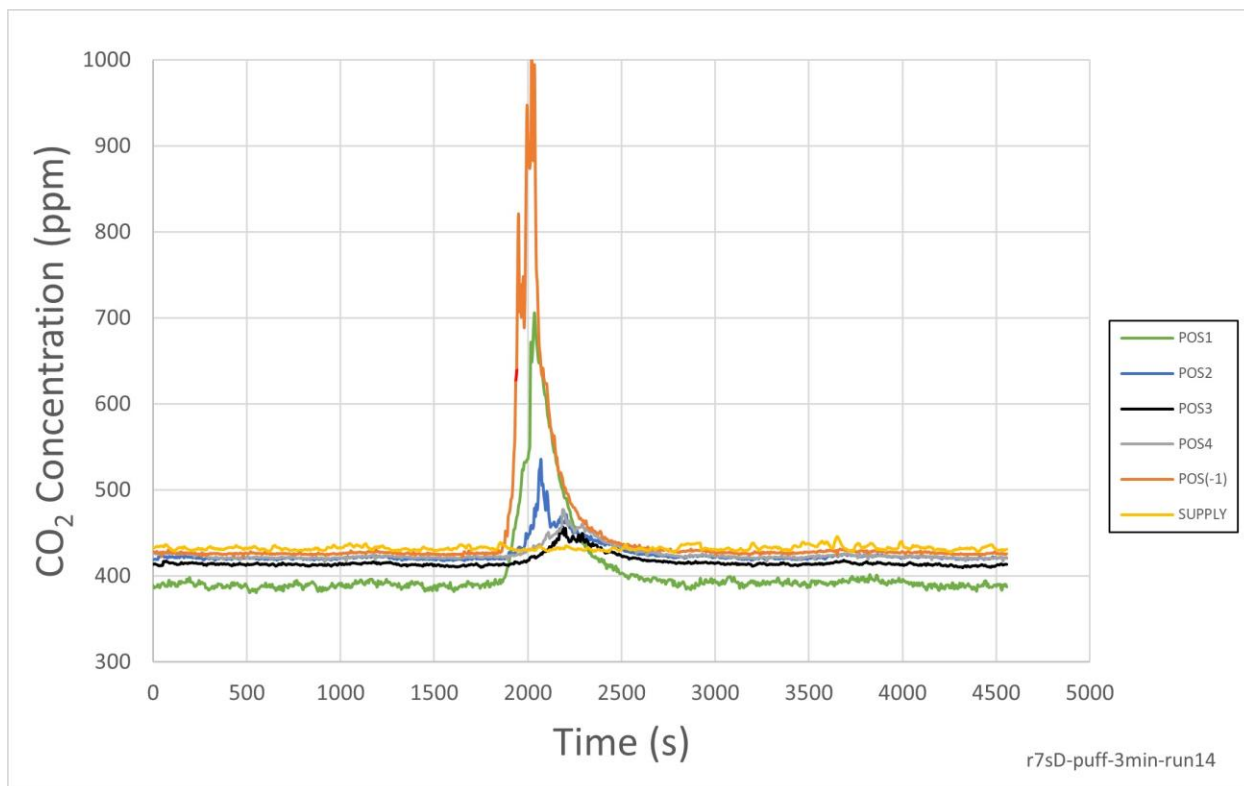
Appendix B B.9: Row 7 Seat D – 3-Minutes Puff – Run 9



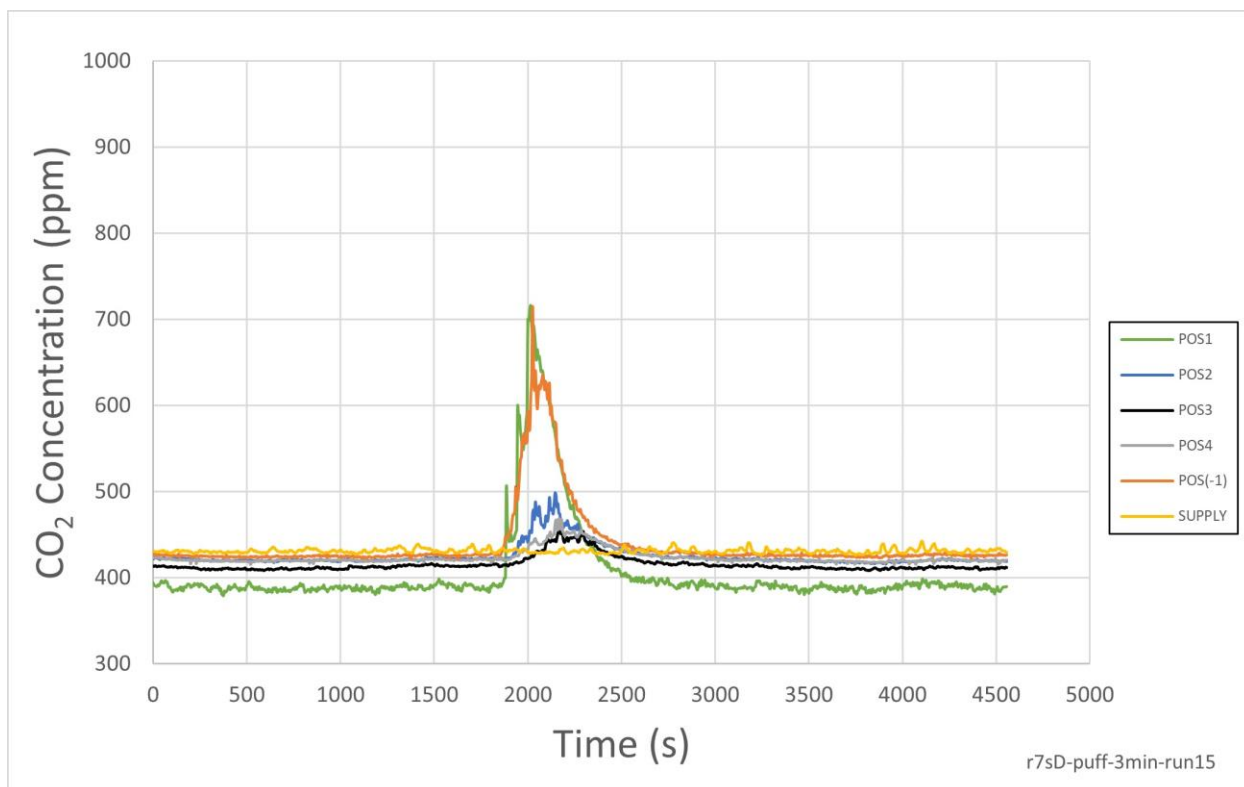
Appendix B B.10: Row 7 Seat D – 3-Minutes Puff – Run 10



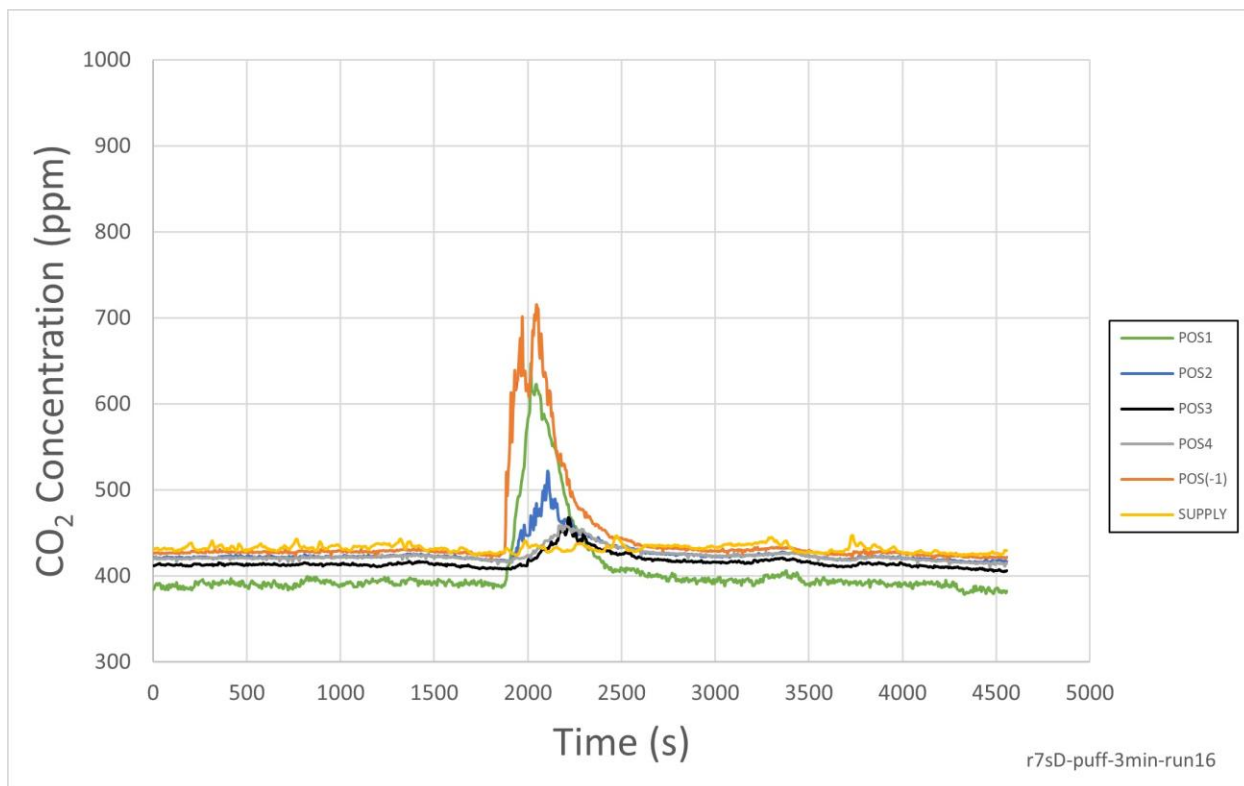
Appendix B B.11: Row 7 Seat D – 3-Minutes Puff – Run 11



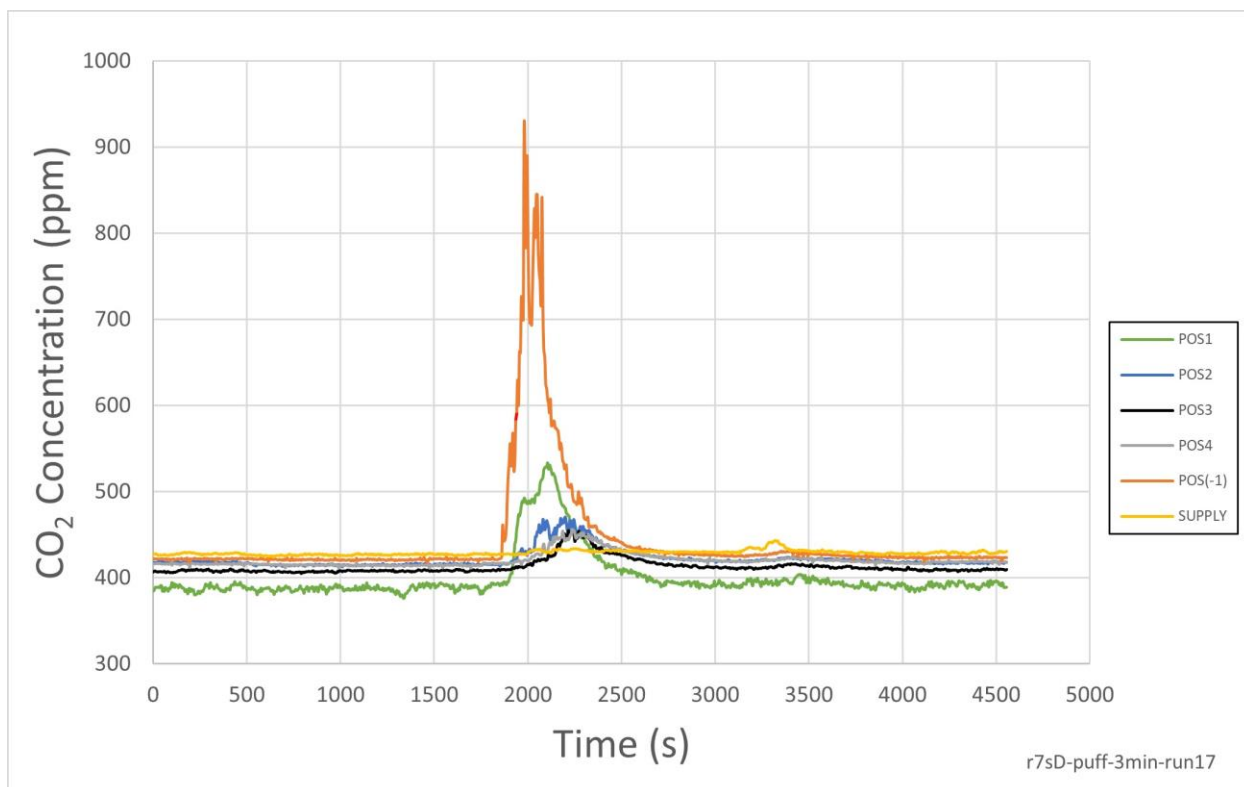
Appendix B B.12: Row 7 Seat D – 3-Minutes Puff – Run 12



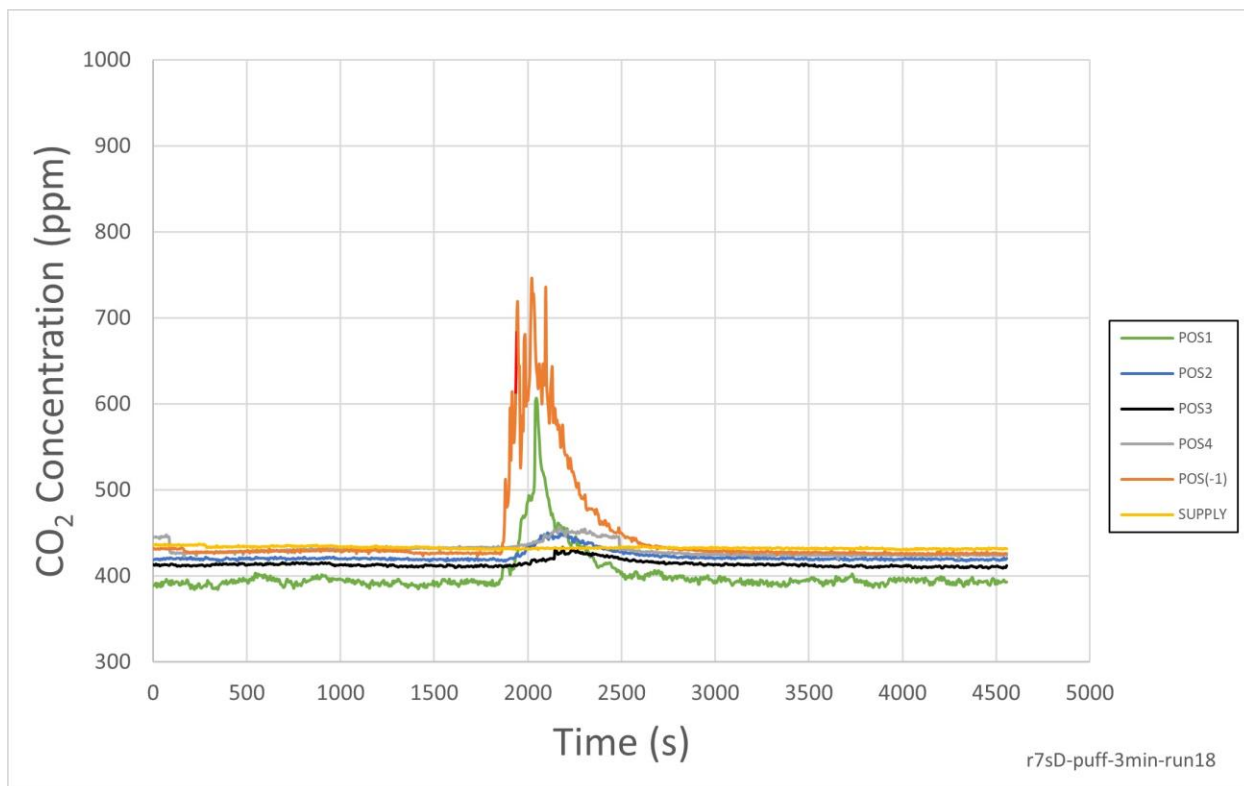
Appendix B B.13: Row 7 Seat D – 3-Minutes Puff – Run 13



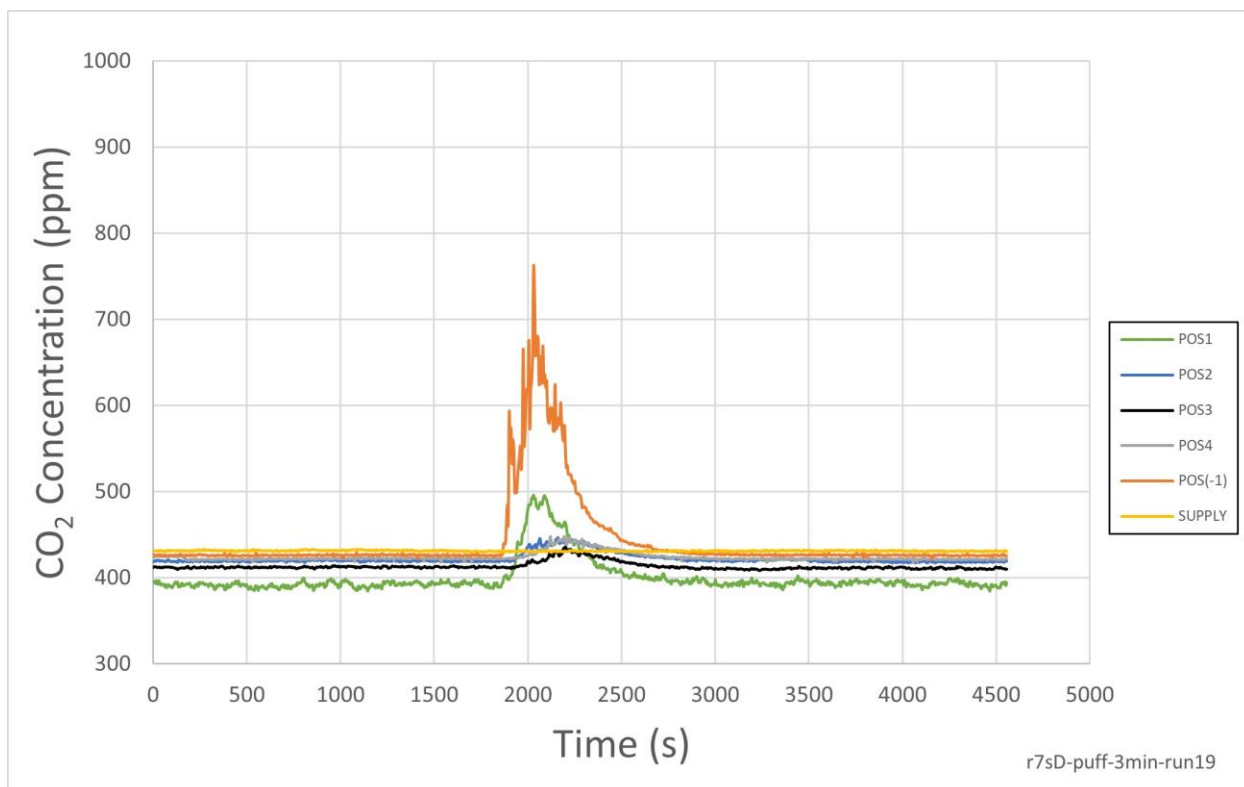
Appendix B B.14: Row 7 Seat D – 3-Minutes Puff – Run 14



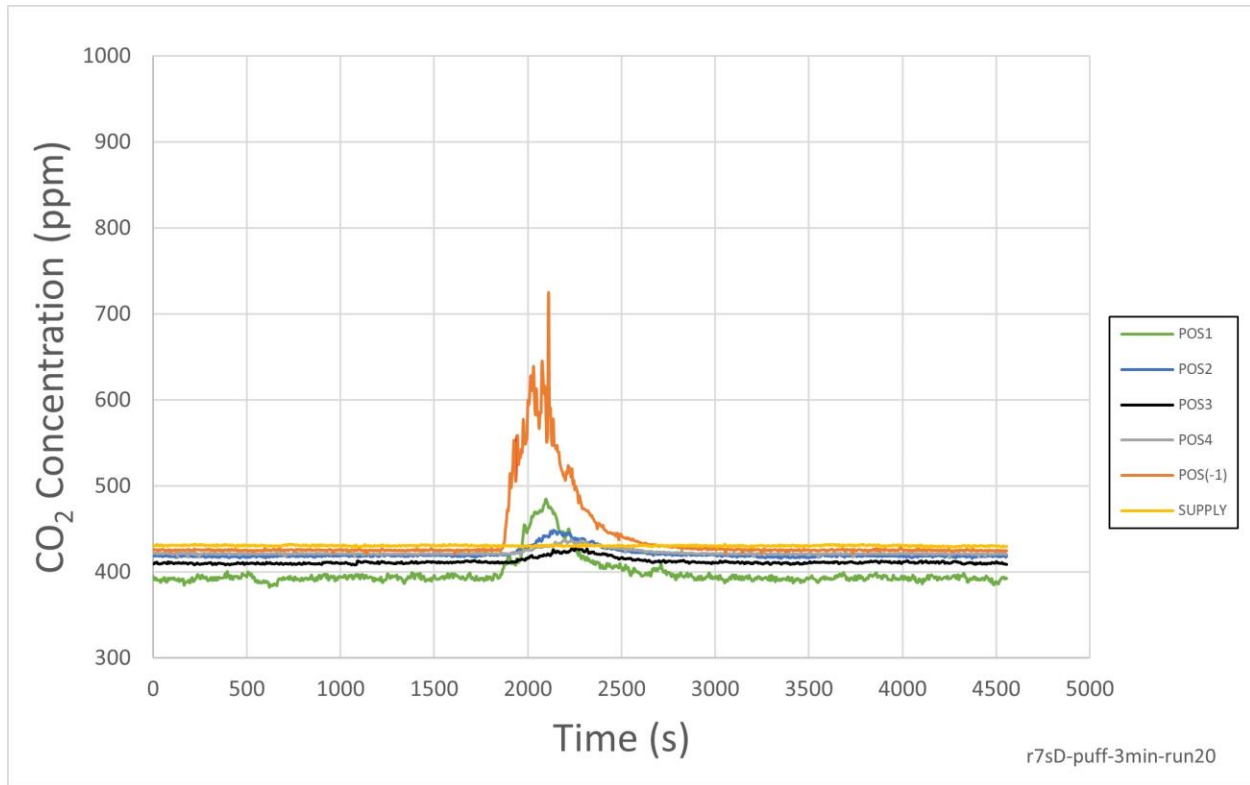
Appendix B B.15: Row 7 Seat D – 3-Minutes Puff – Run 15



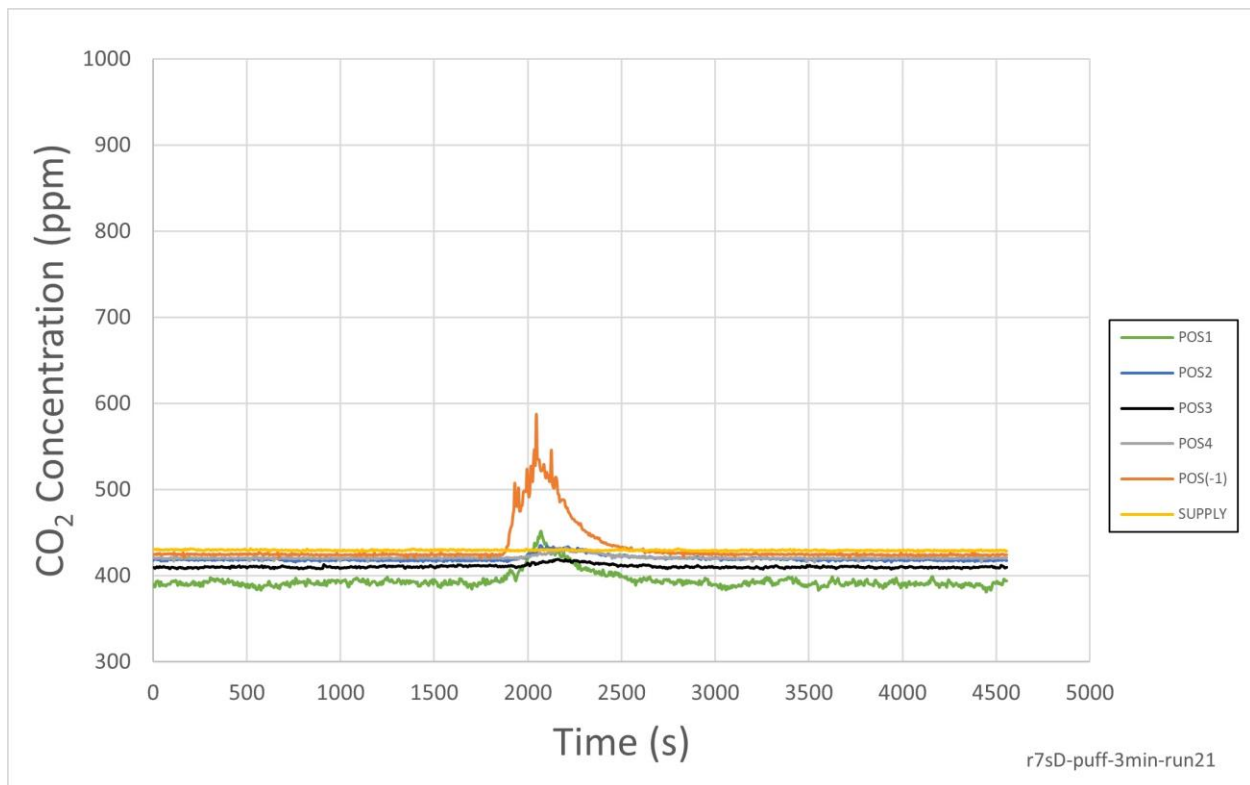
Appendix B B.16: Row 7 Seat D – 3-Minutes Puff – Run 16



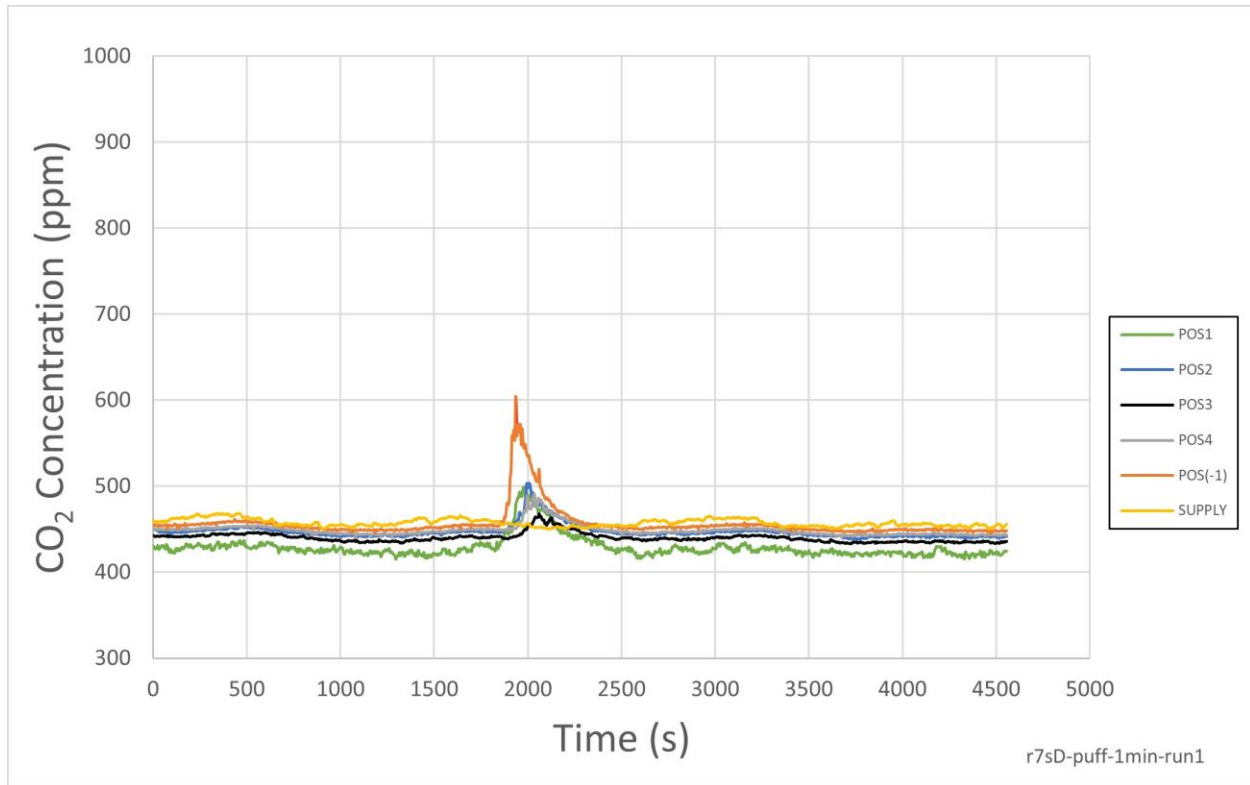
Appendix B B.17: Row 7 Seat D – 3-Minutes Puff – Run 17



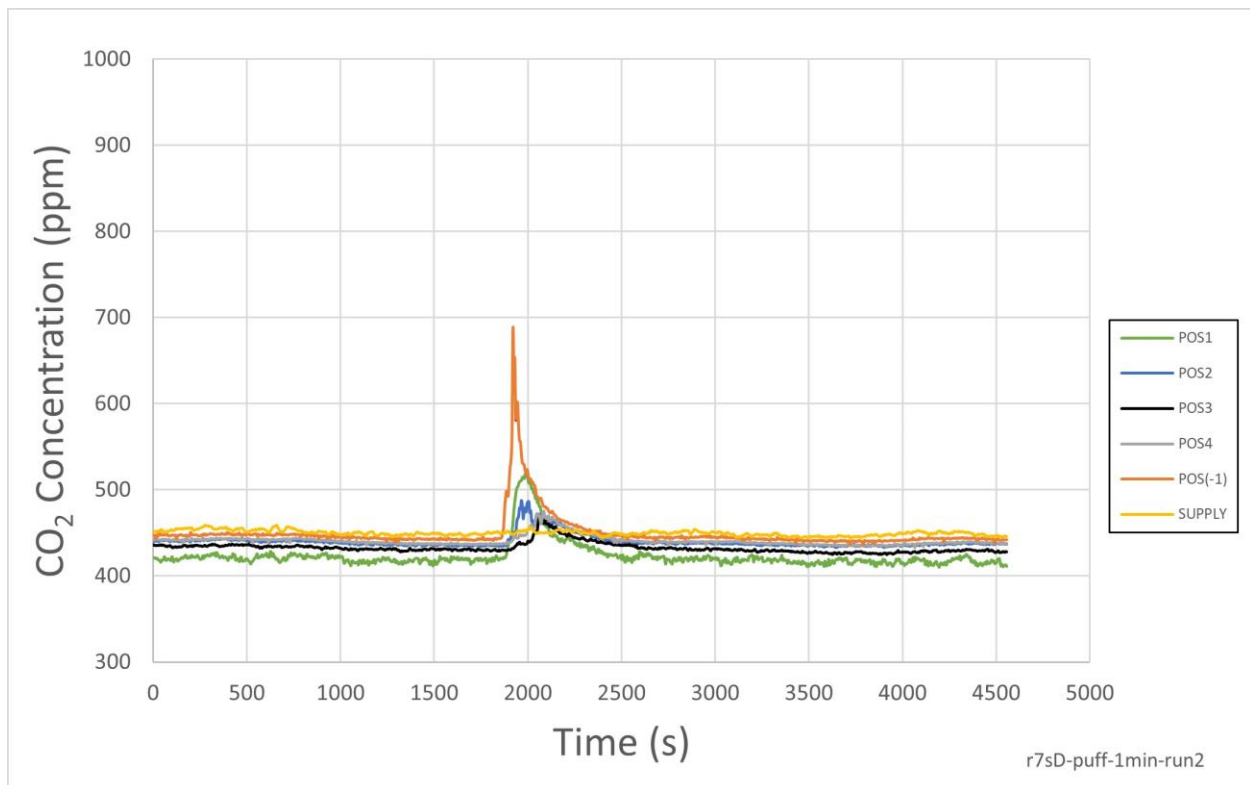
Appendix B B.18: Row 7 Seat D – 3-Minutes Puff – Run 18



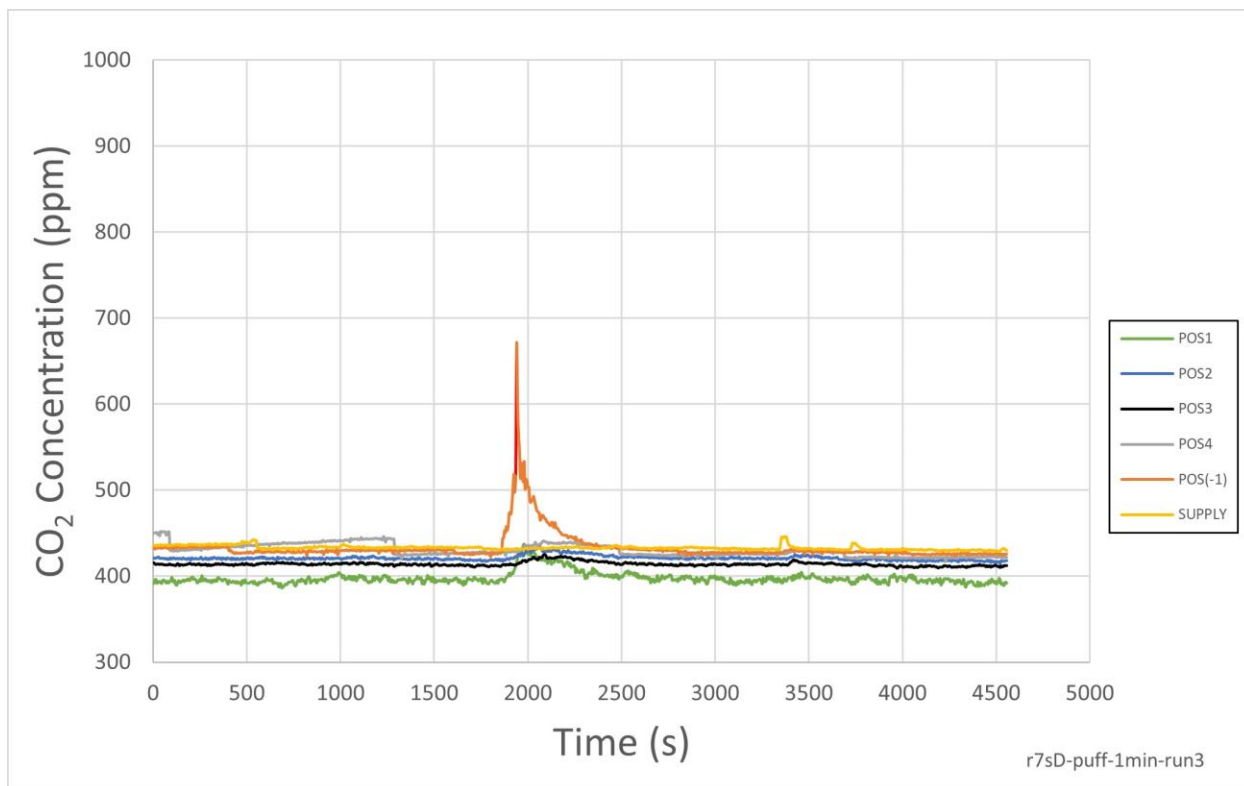
Appendix B B.19: Row 7 Seat D – 3-Minutes Puff – Run 19



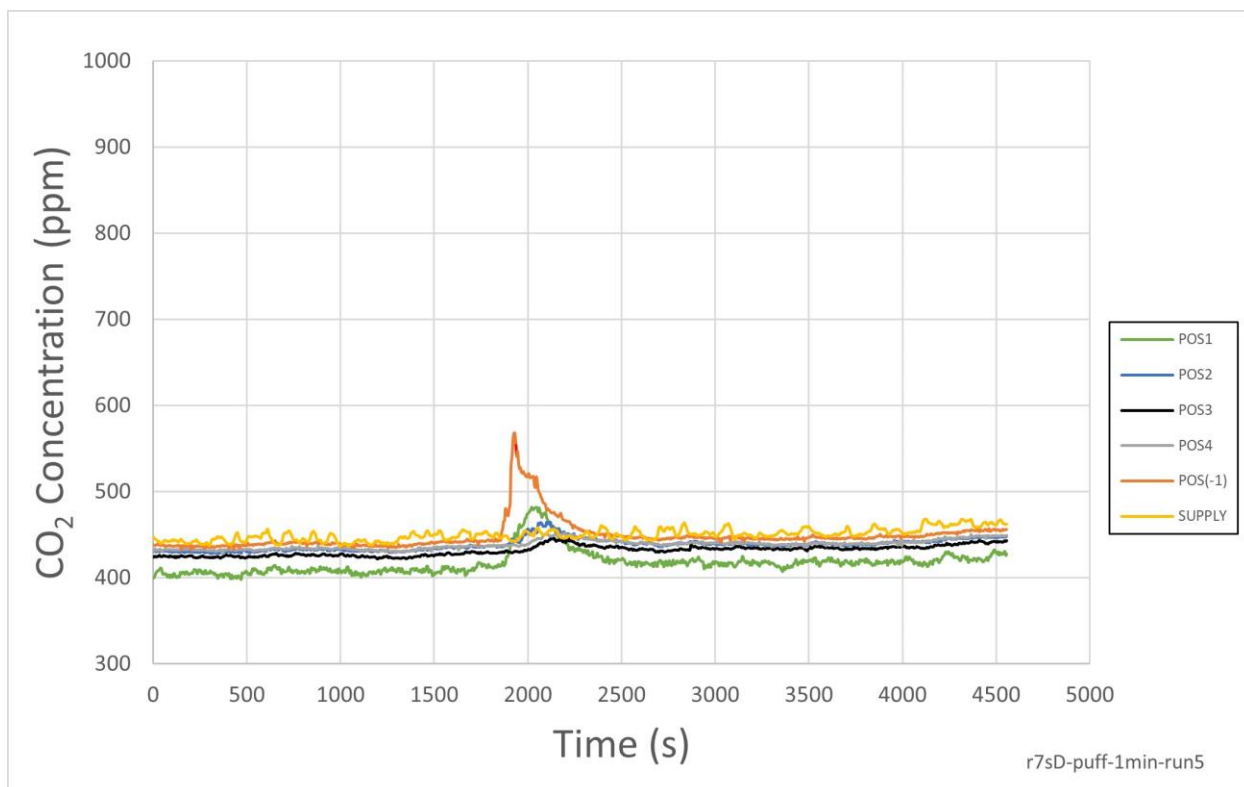
Appendix B B.20: Row 7 Seat D – 1-Minute Puff – Run 1



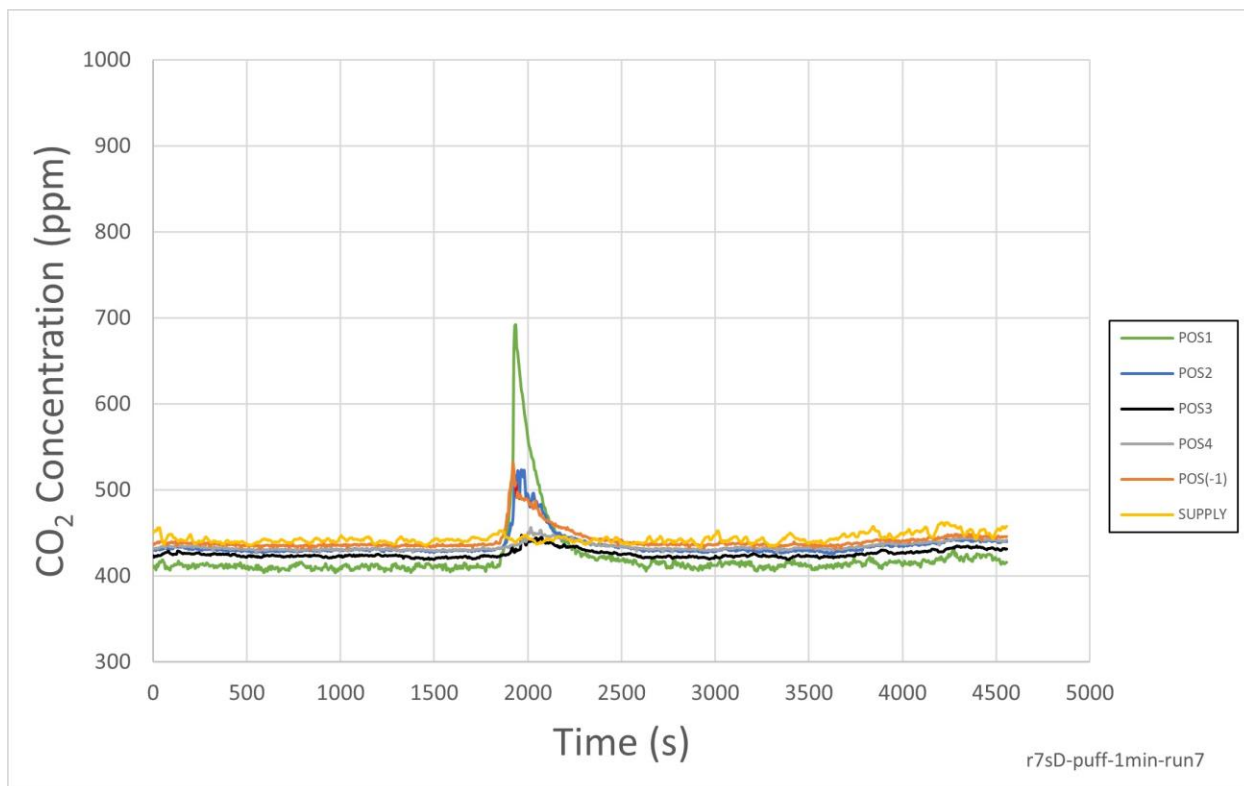
Appendix B B.21: Row 7 Seat D – 1-Minute Puff – Run 2



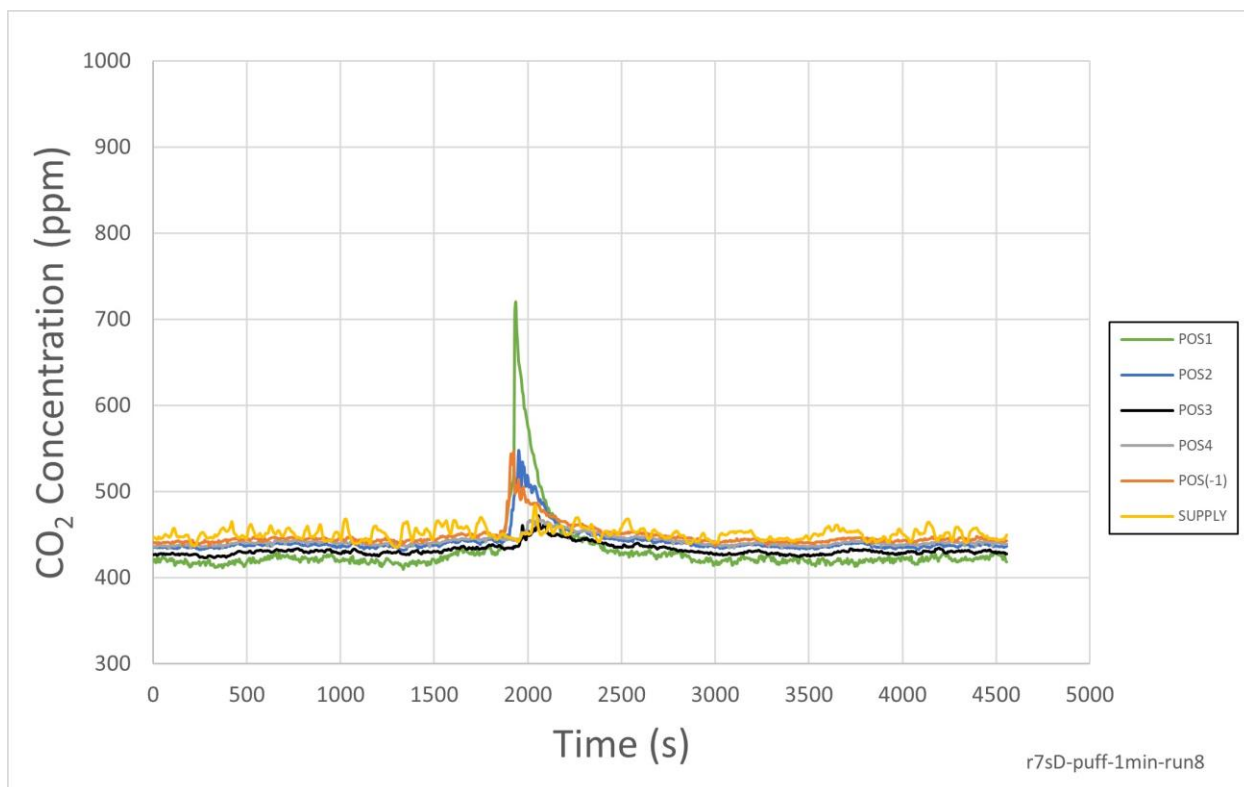
Appendix B B.22: Row 7 Seat D – 1-Minute Puff – Run 3



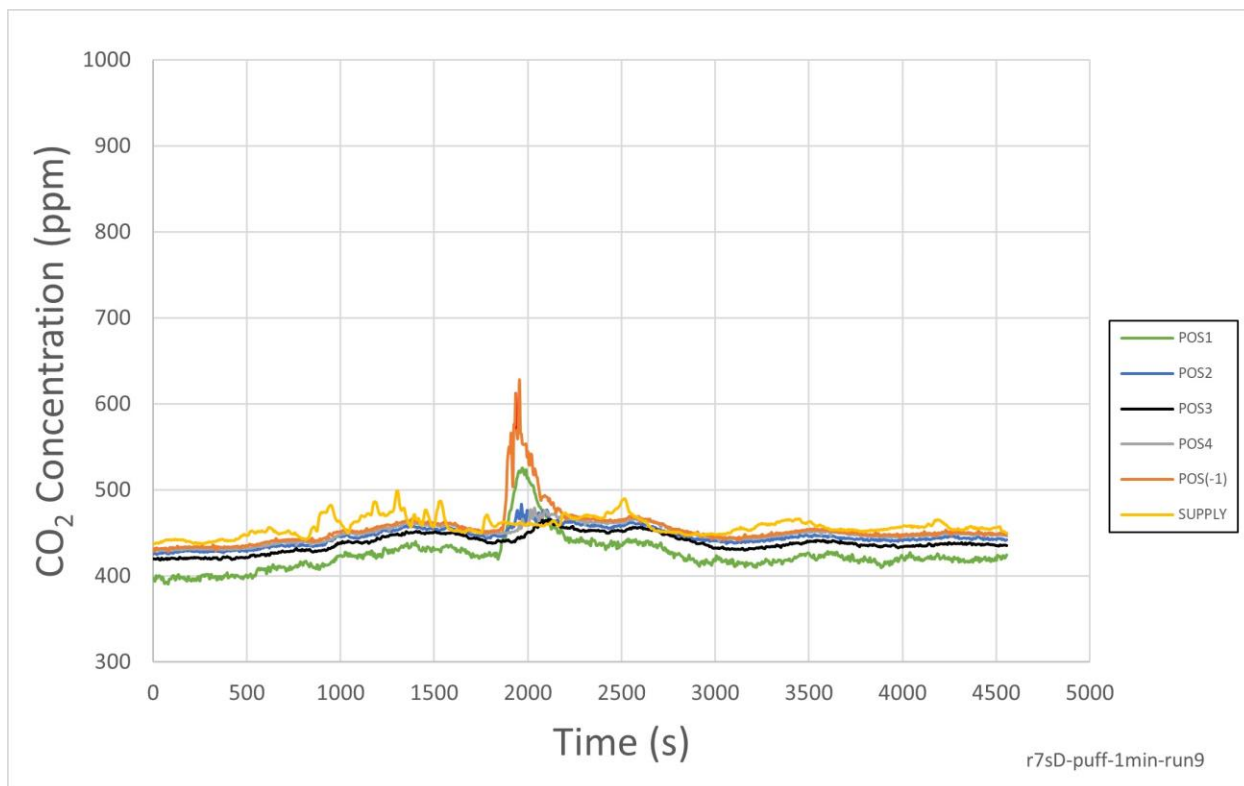
Appendix B B.23: Row 7 Seat D – 1-Minute Puff – Run 4



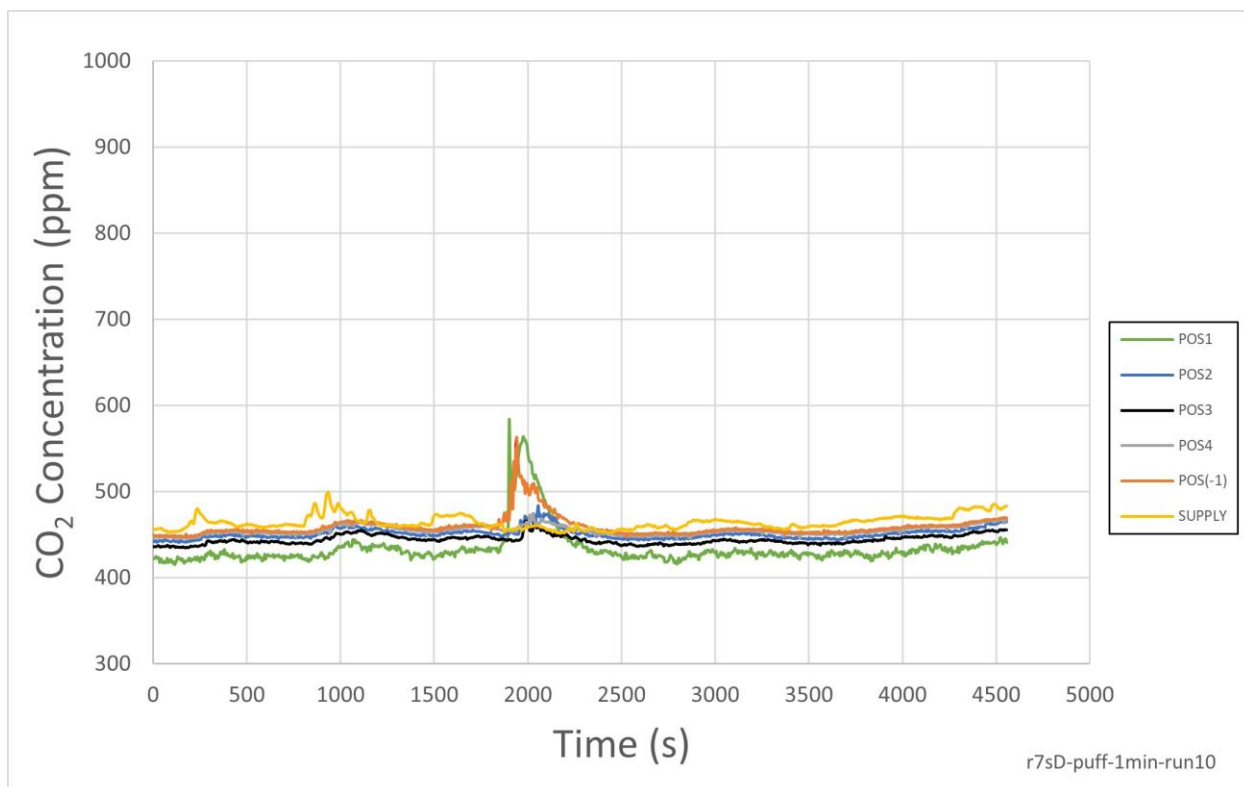
Appendix B B.24: Row 7 Seat D – 1-Minute Puff – Run 5



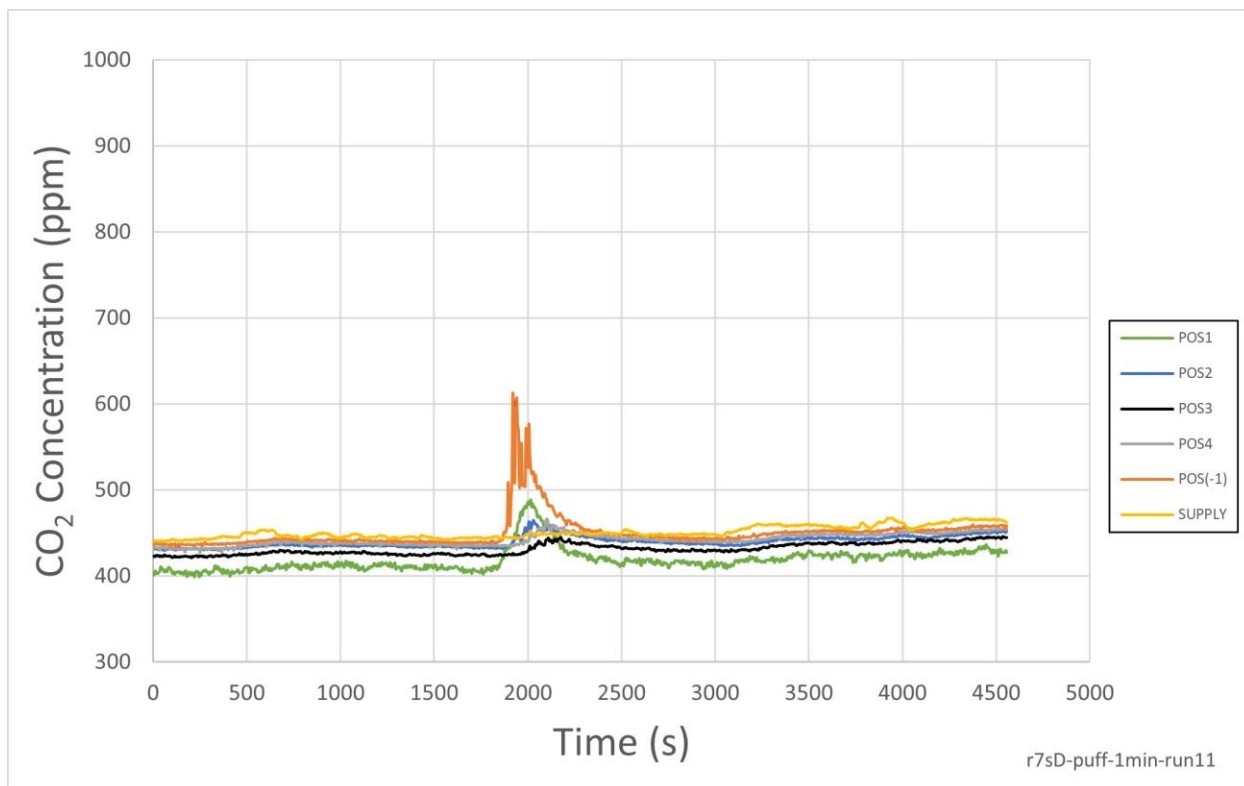
Appendix B B.25: Row 7 Seat D – 1-Minute Puff – Run 6



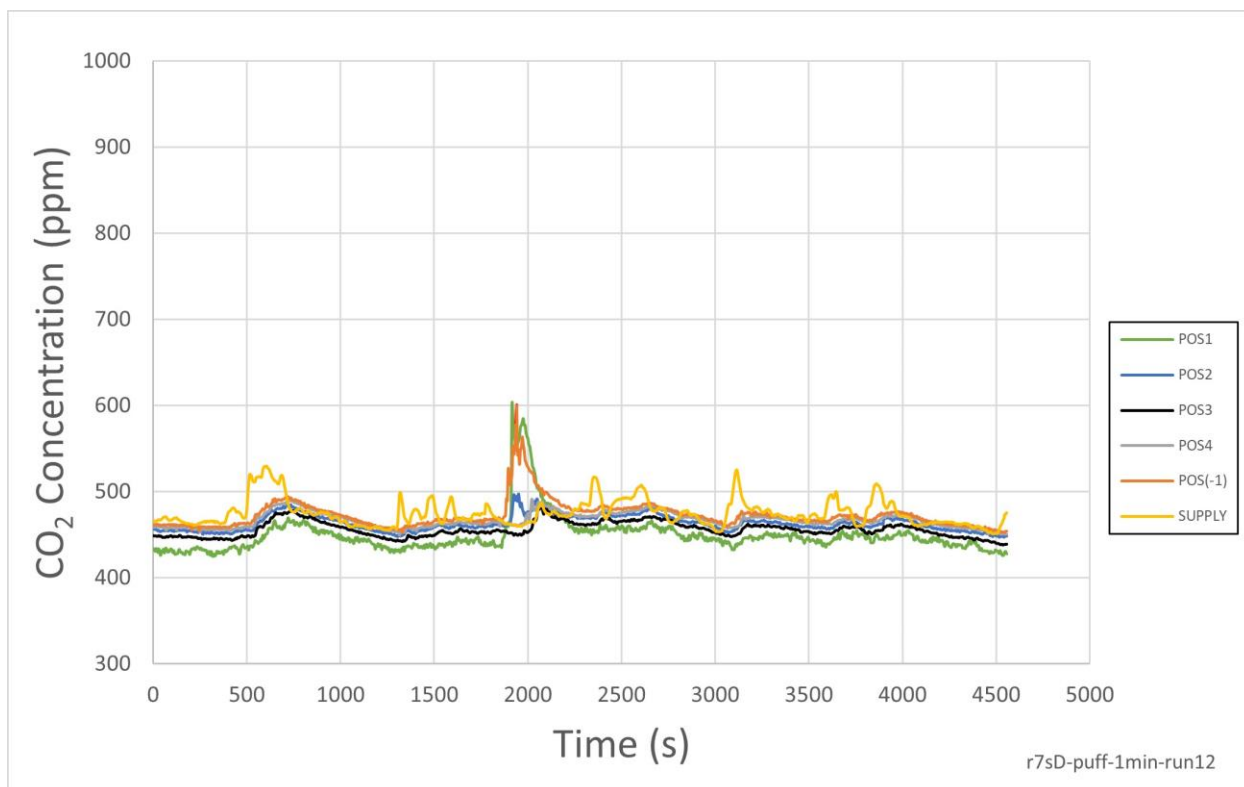
Appendix B B.26: Row 7 Seat D – 1-Minute Puff – Run 7



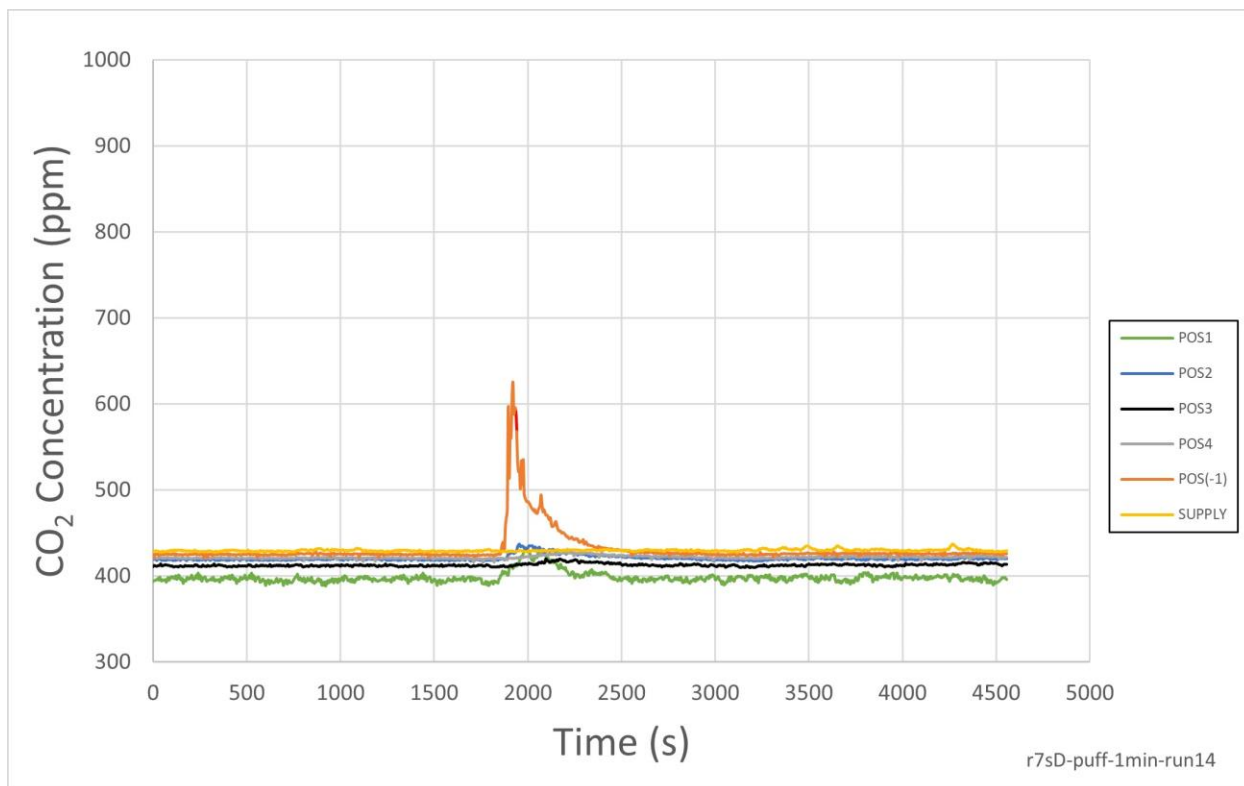
Appendix B B.27: Row 7 Seat D – 1-Minute Puff – Run 8



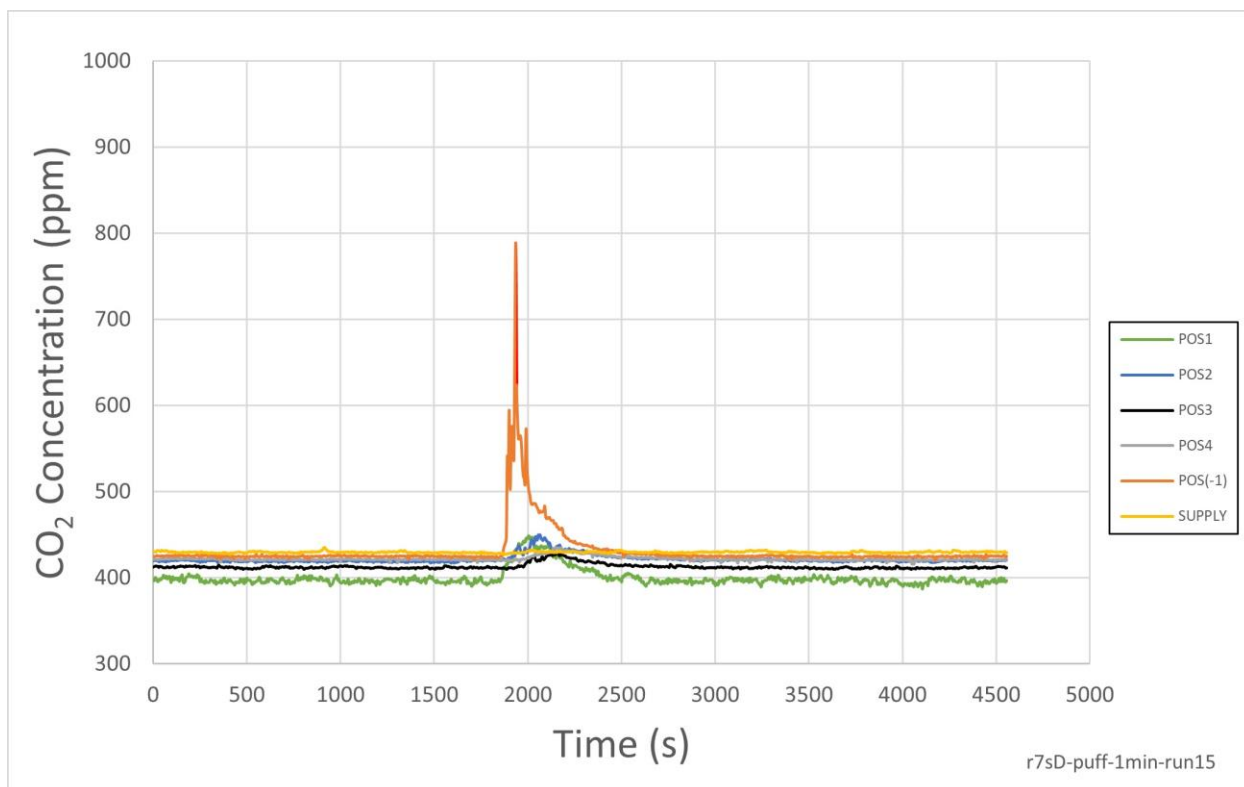
Appendix B B.28: Row 7 Seat D – 1-Minute Puff – Run 9



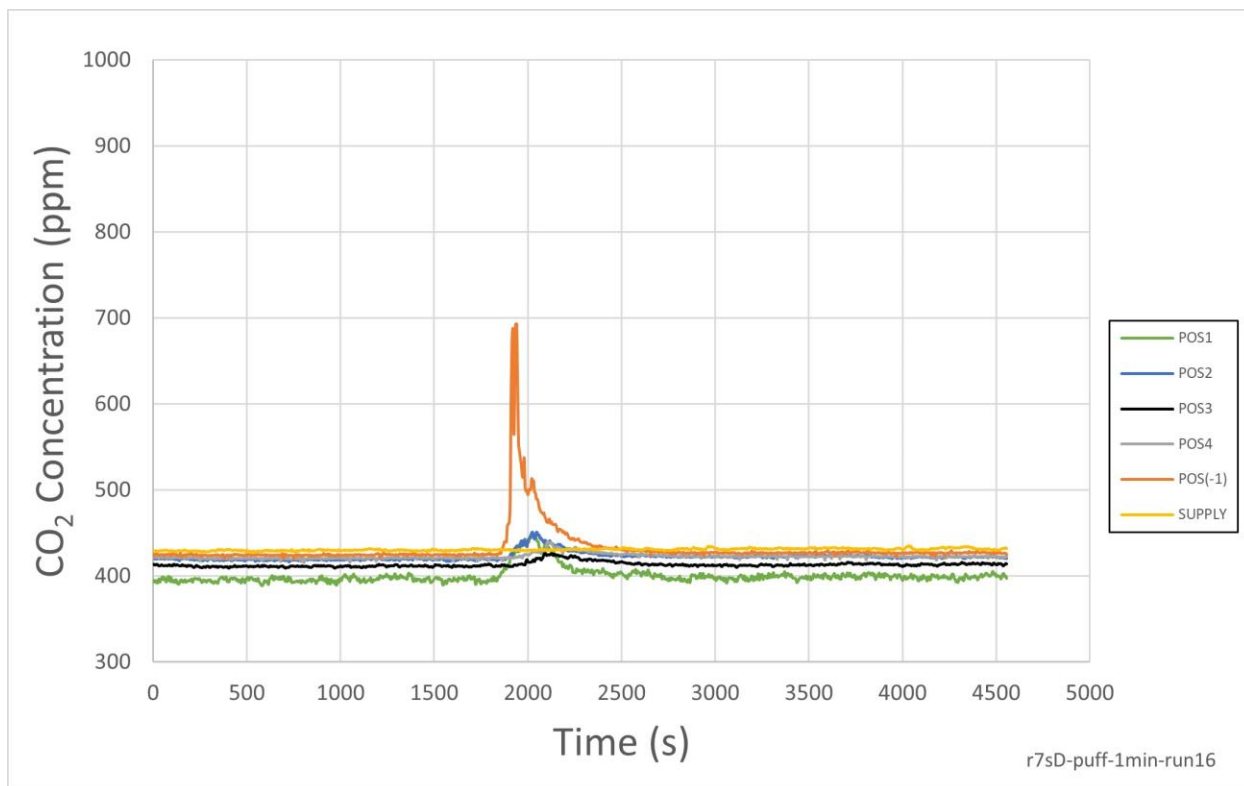
Appendix B B.29: Row 7 Seat D – 1-Minute Puff – Run 10



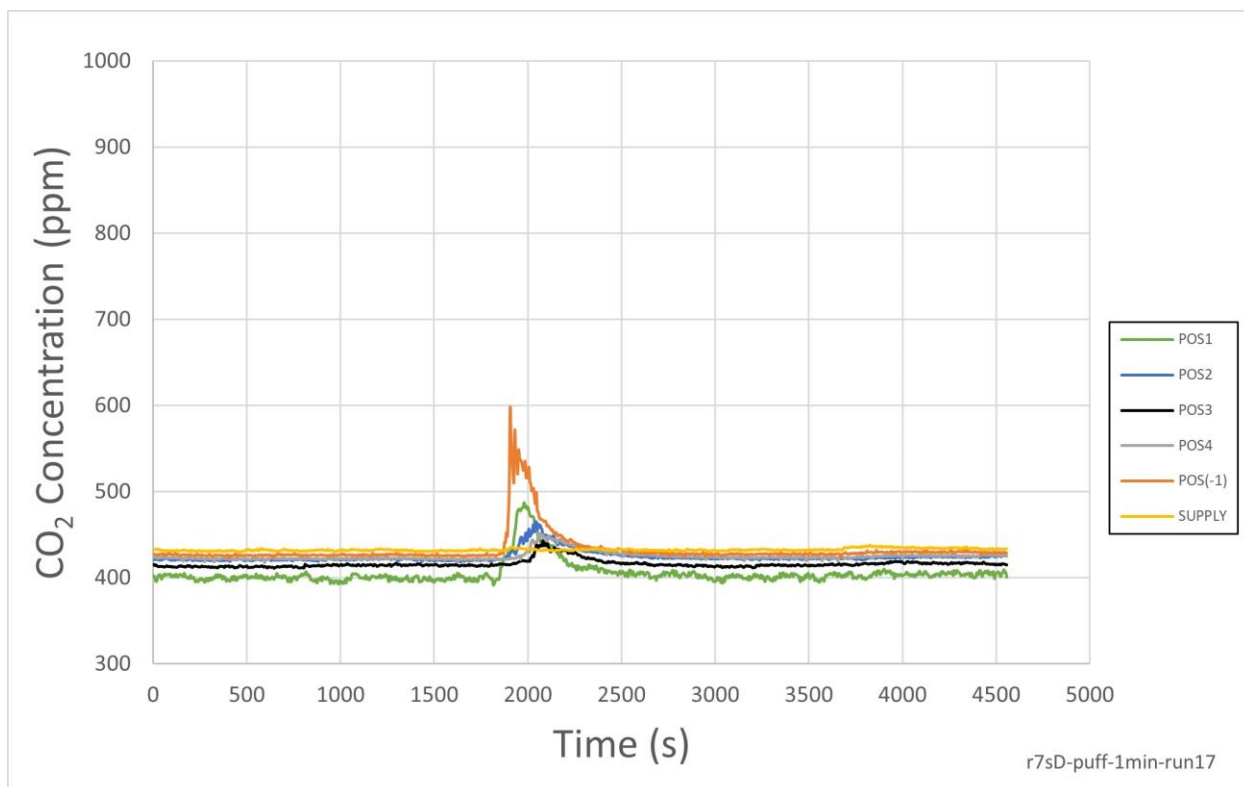
Appendix B B.30: Row 7 Seat D – 1-Minute Puff – Run 11



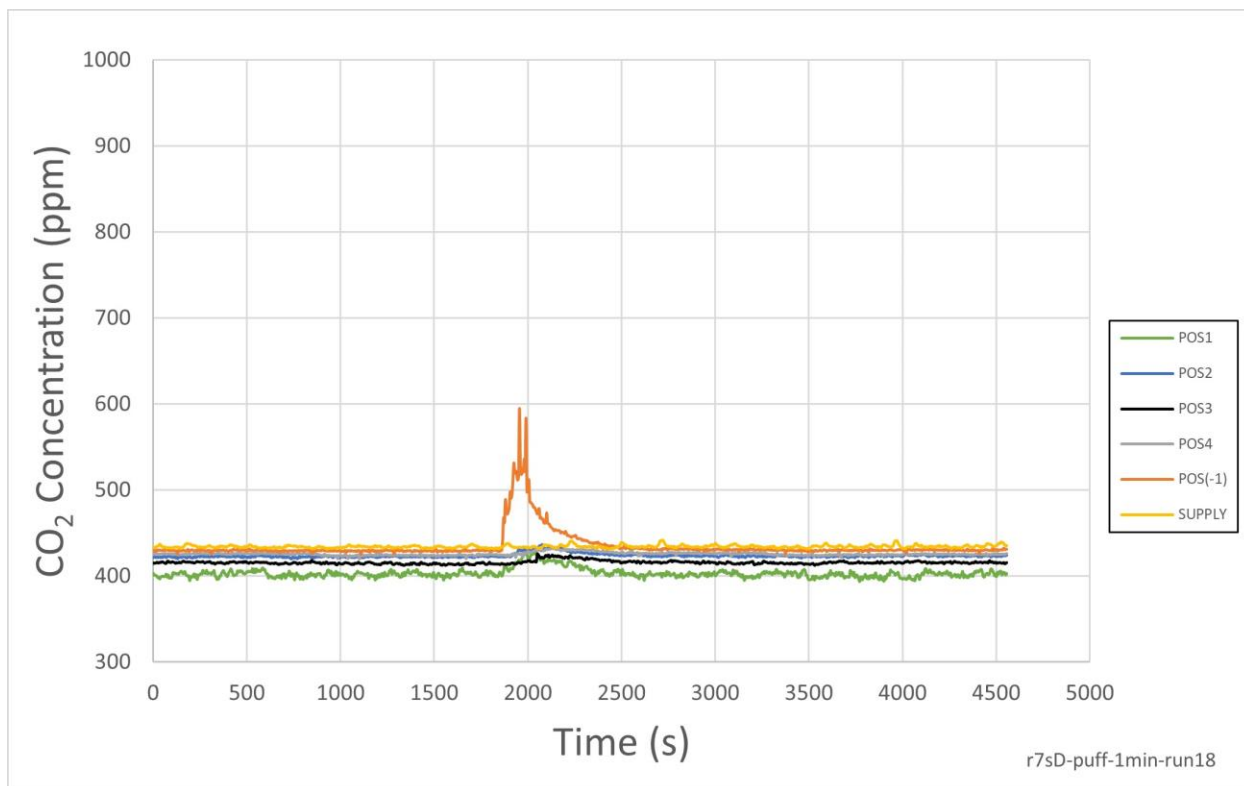
Appendix B B.31: Row 7 Seat D – 1-Minute Puff – Run 12



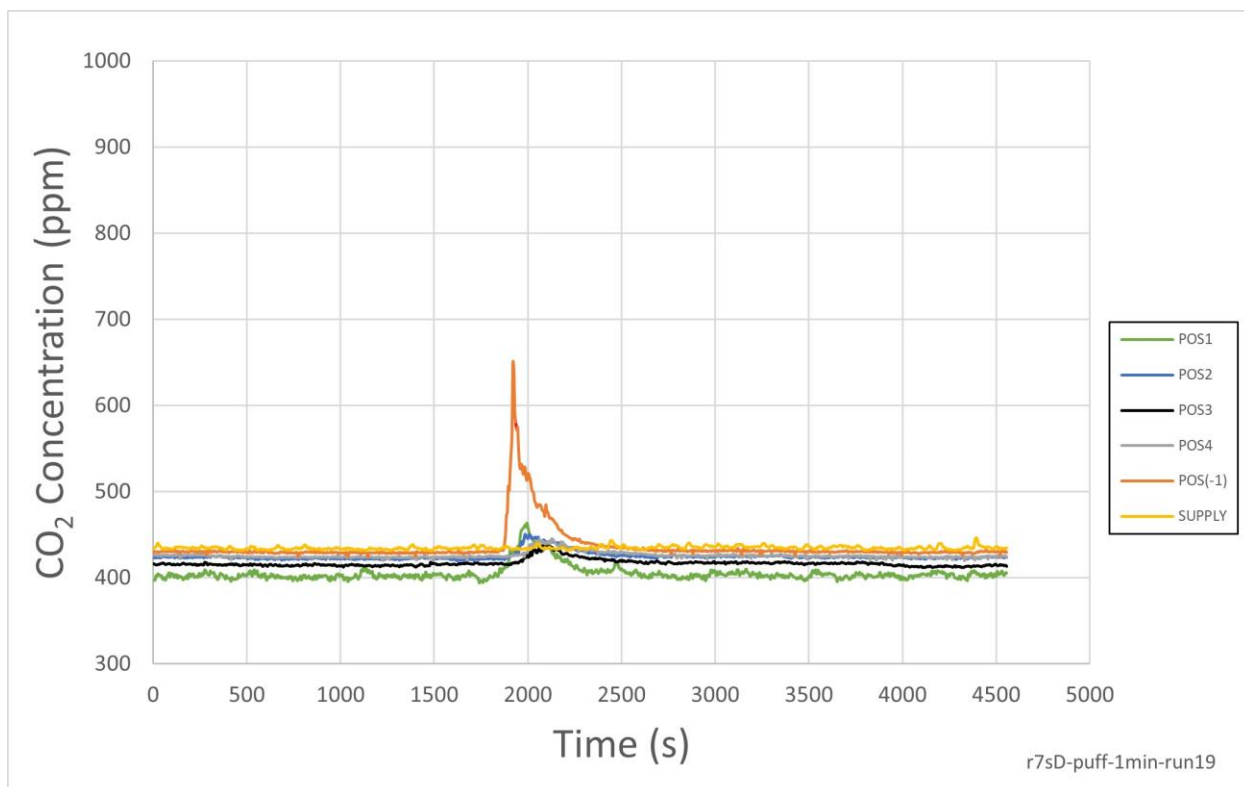
Appendix B B.32: Row 7 Seat D – 1-Minute Puff – Run 13



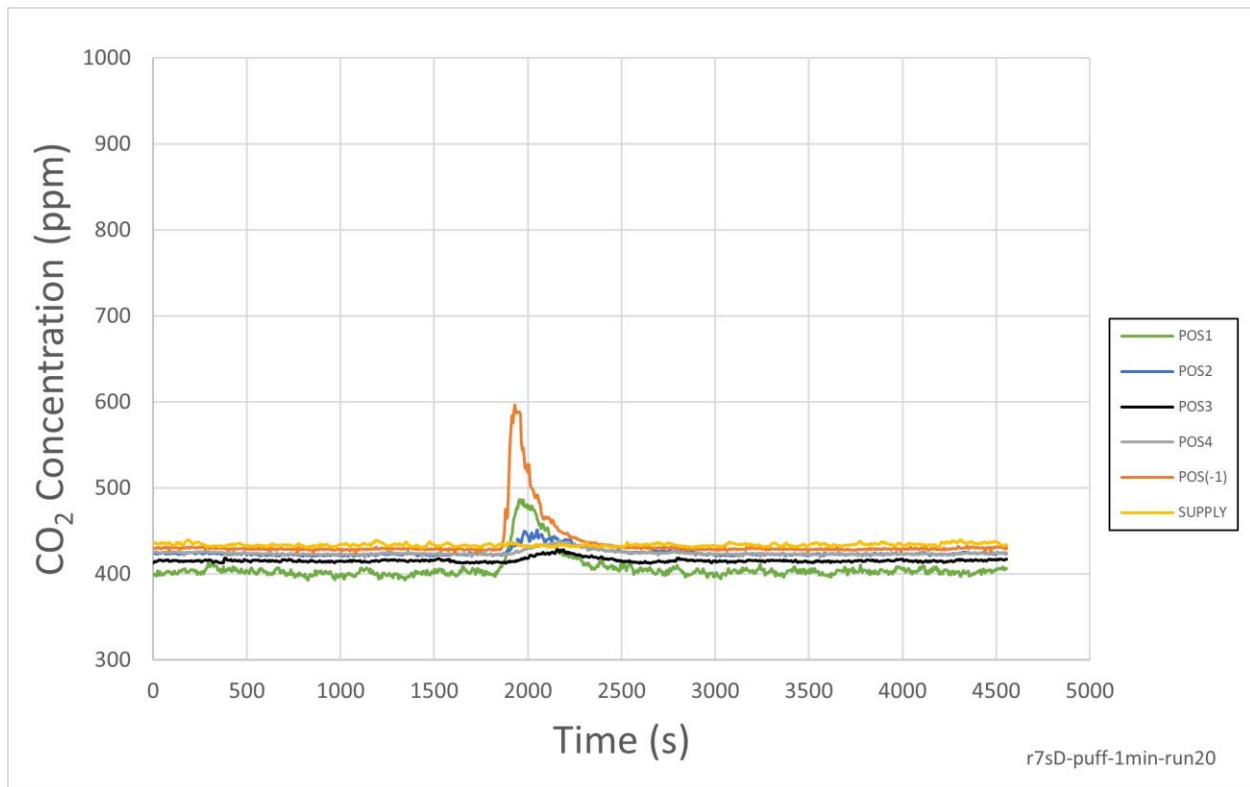
Appendix B B.33: Row 7 Seat D – 1-Minute Puff – Run 14



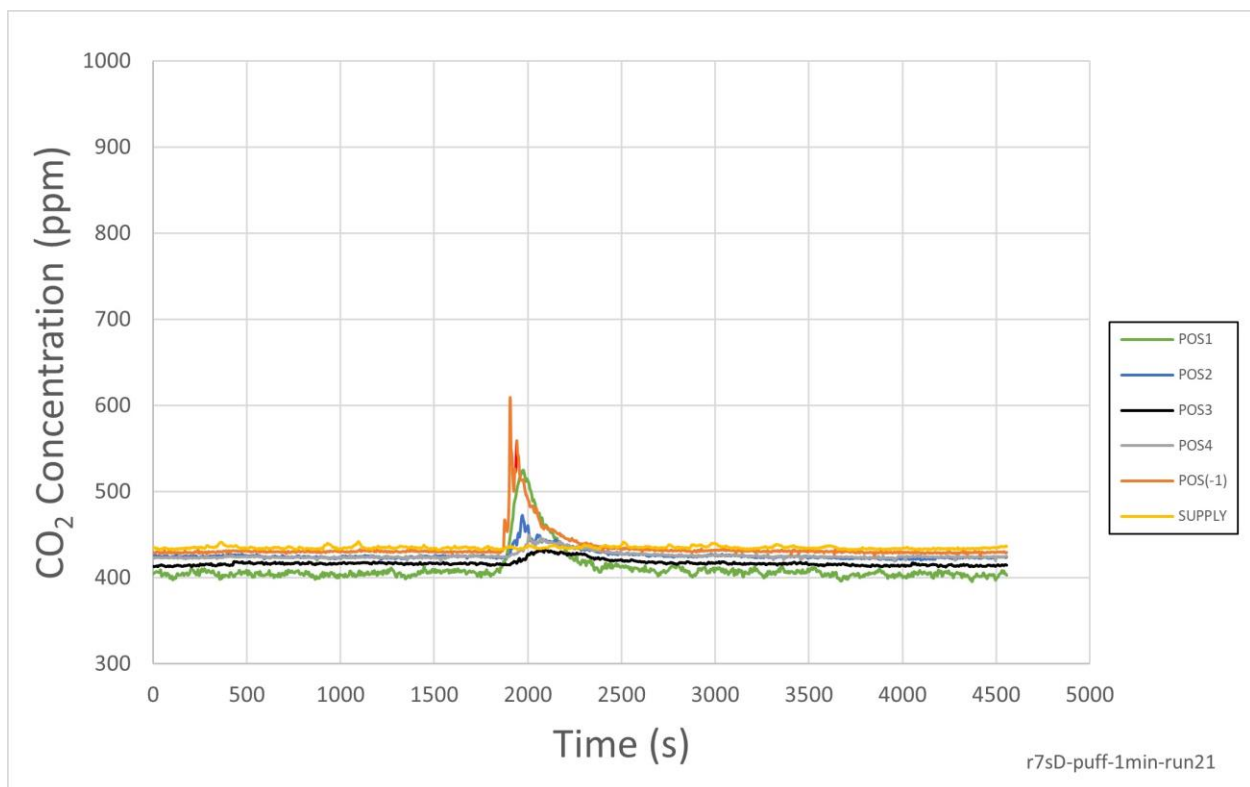
Appendix B B.34: Row 7 Seat D – 1-Minute Puff – Run 15



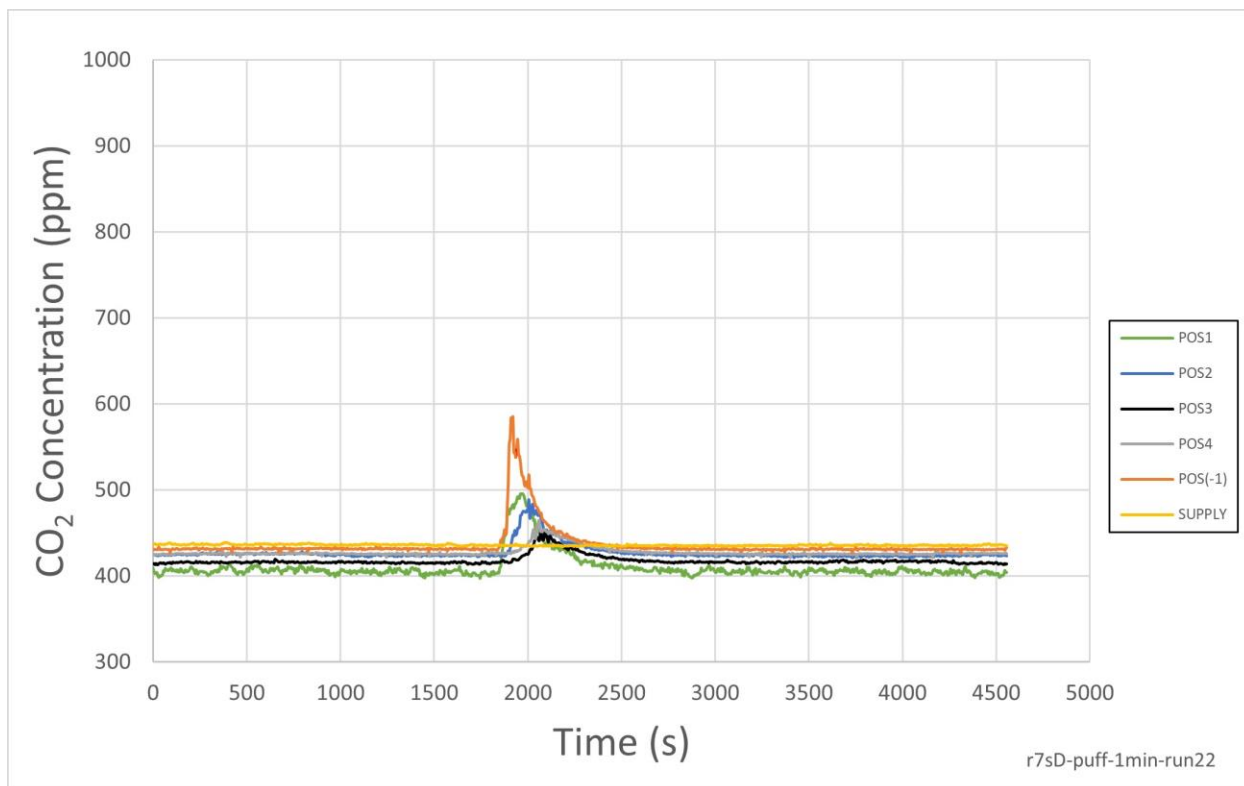
Appendix B B.35: Row 7 Seat D – 1-Minute Puff – Run 16



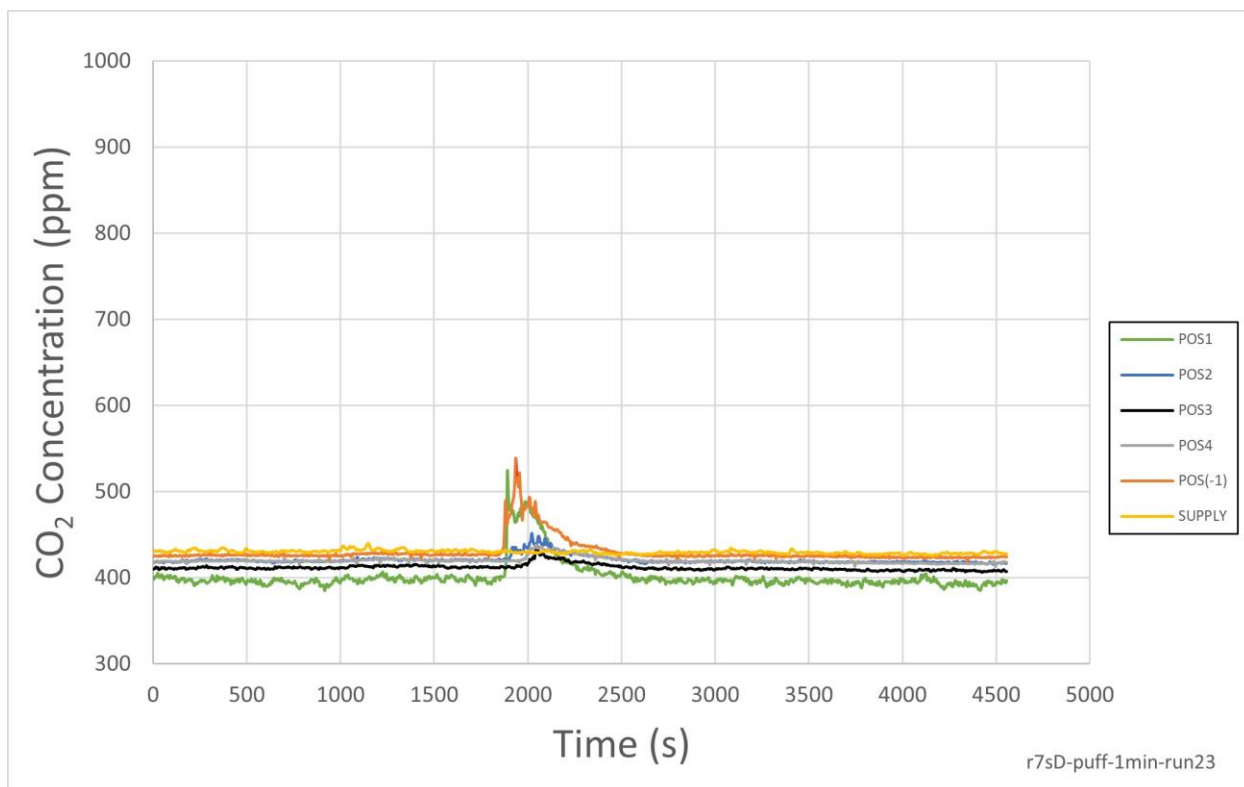
Appendix B B.36: Row 7 Seat D – 1-Minute Puff – Run 17



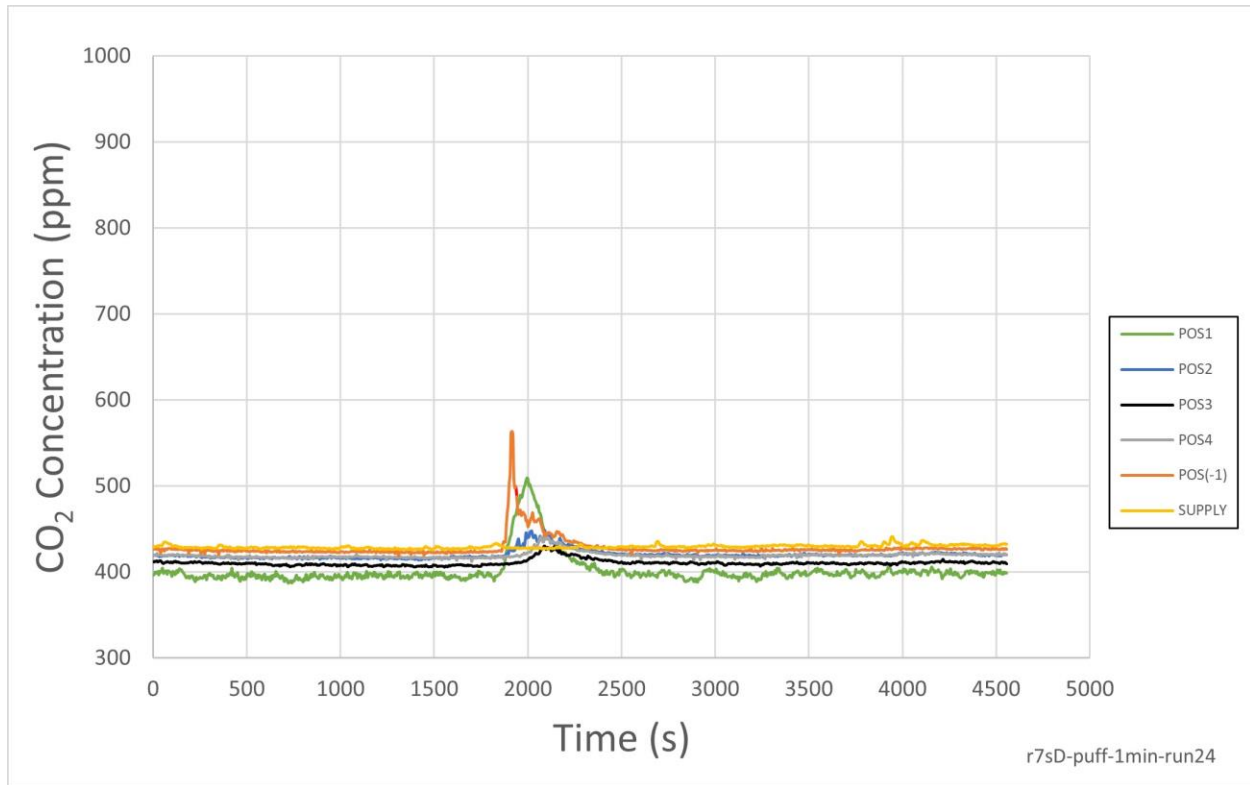
Appendix B B.37: Row 7 Seat D – 1-Minute Puff – Run 18



Appendix B B.38: Row 7 Seat D – 1-Minute Puff – Run 19

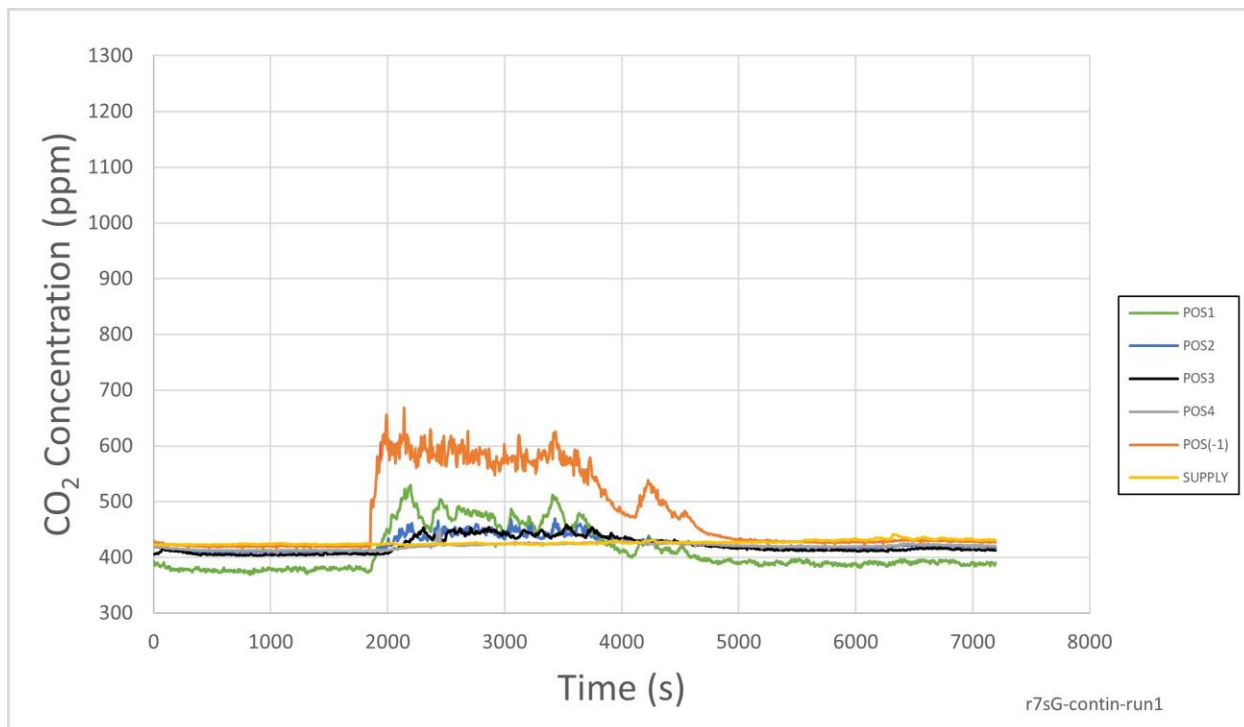


Appendix B B.39: Row 7 Seat D – 1-Minute Puff – Run 20

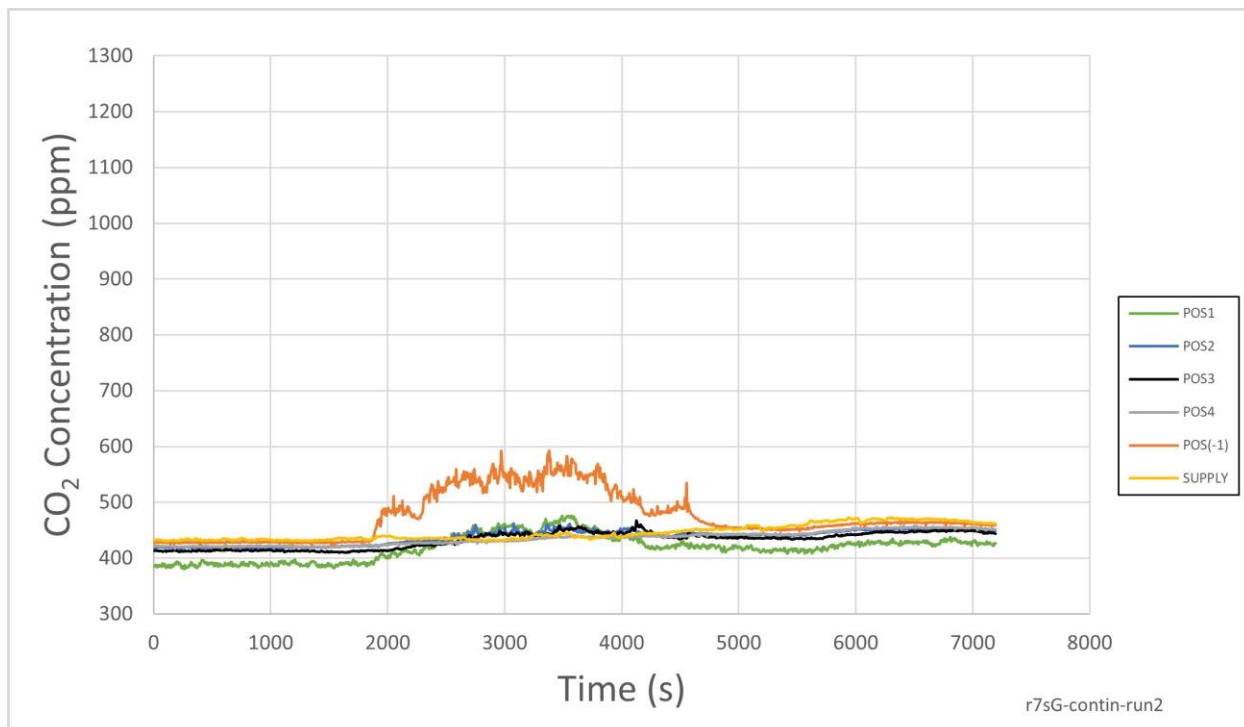


Appendix B B.40: Row 7 Seat D – 1-Minute Puff – Run 21

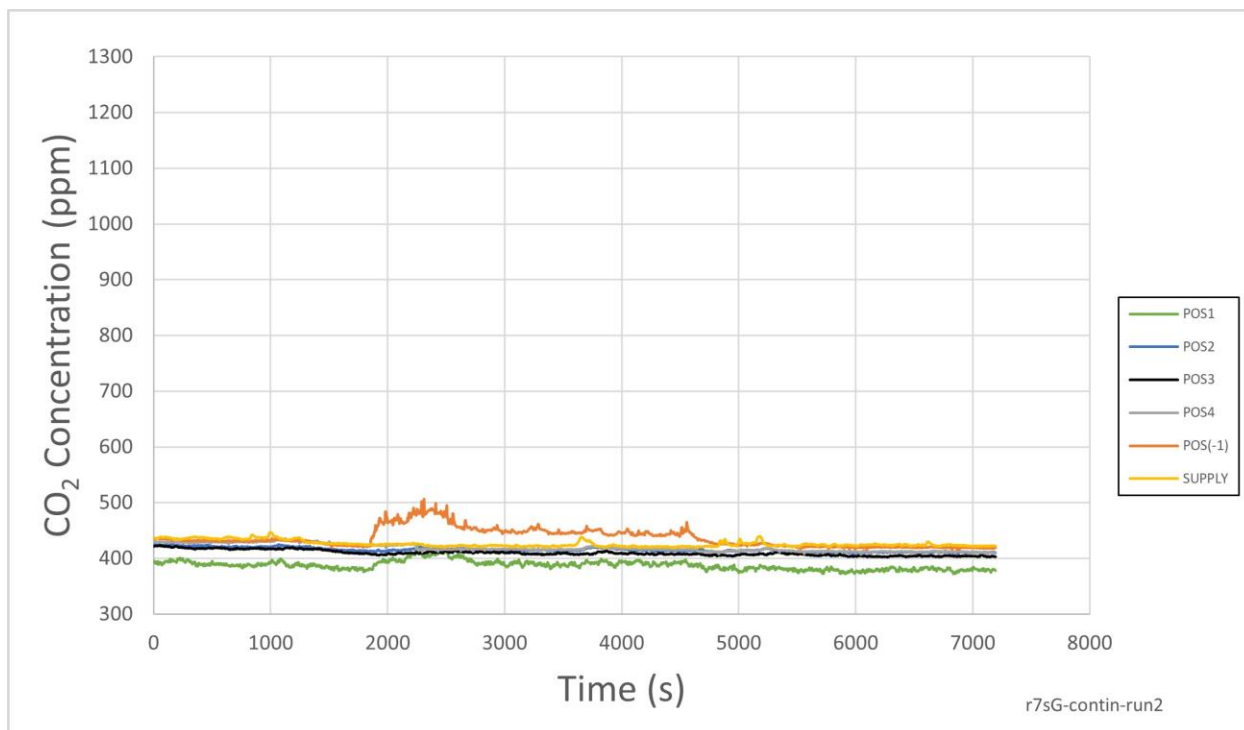
Appendix C - Row 7 Seat G – Continuous Injection Responses



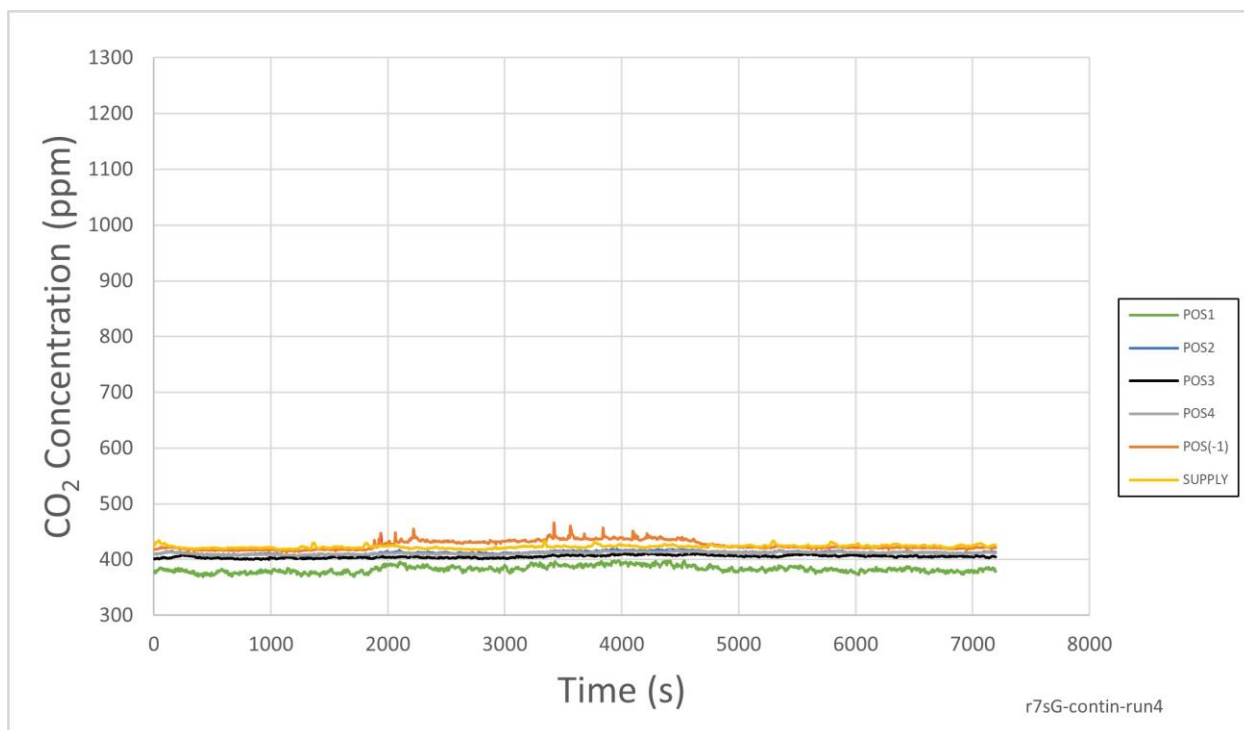
Appendix C C.1: Row 7 Seat G – Continuous – Run 1



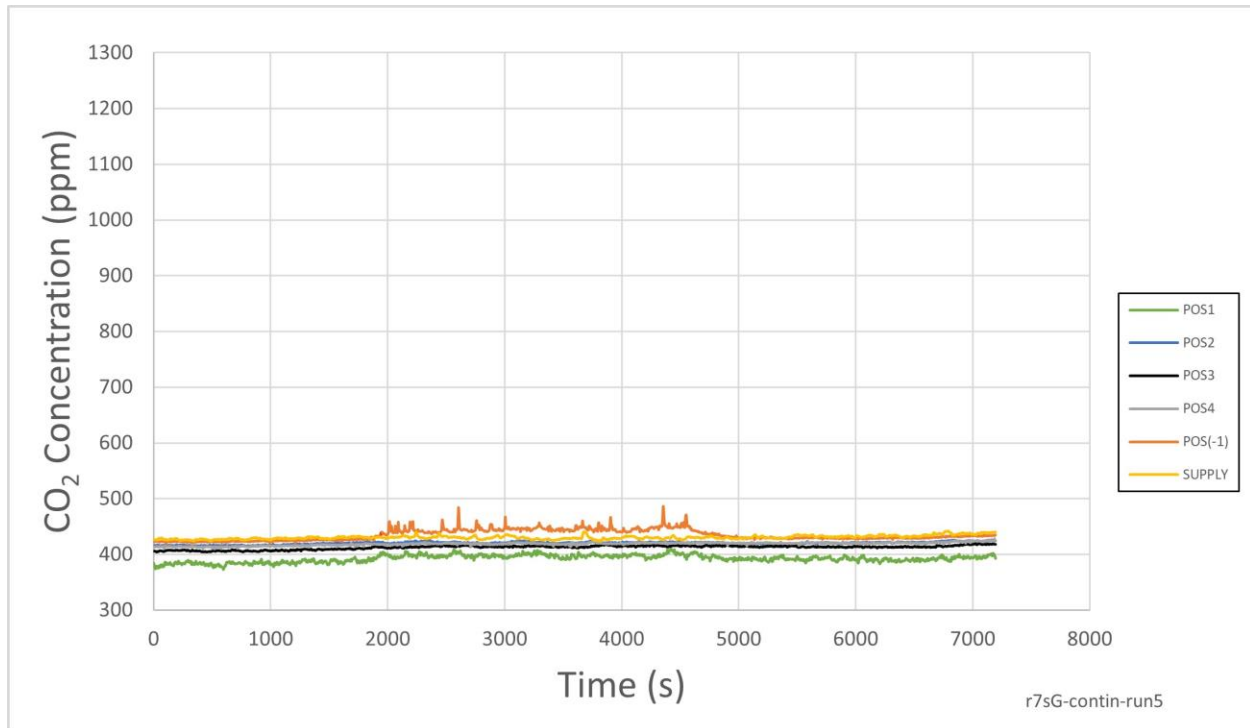
Appendix C C.2: Row 7 Seat G – Continuous – Run 2



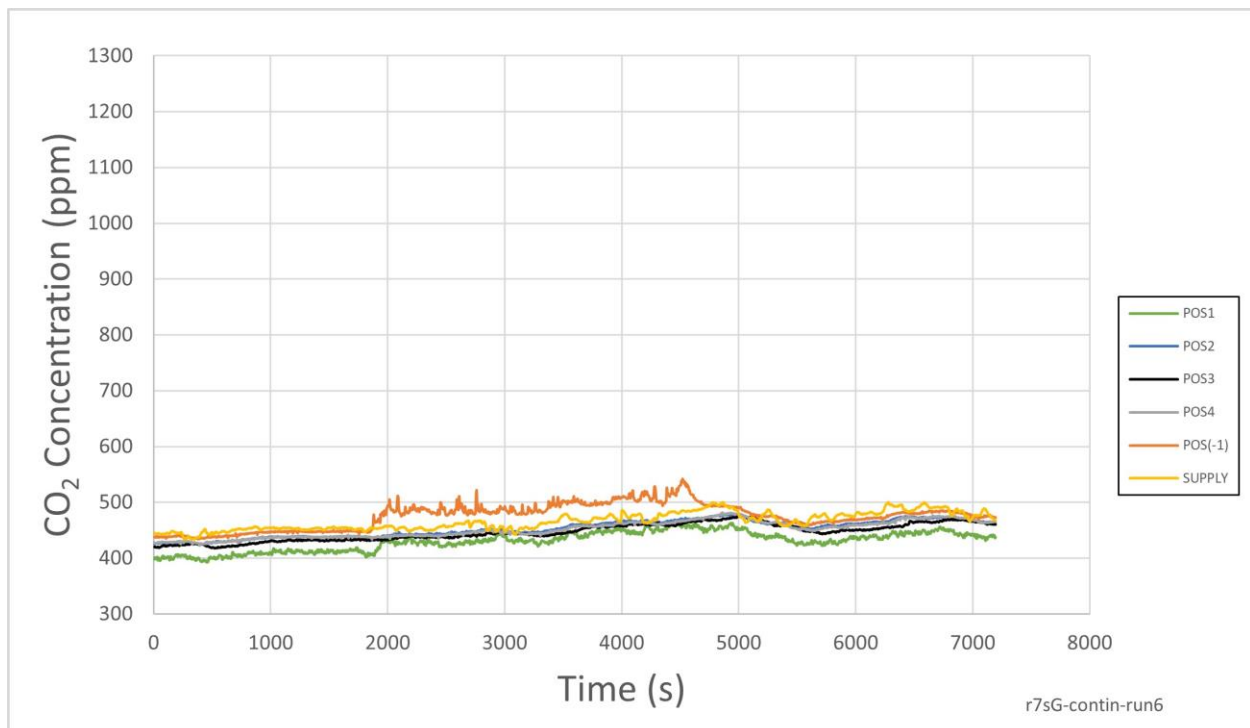
Appendix C C.3: Row 7 Seat G – Continuous – Run 3



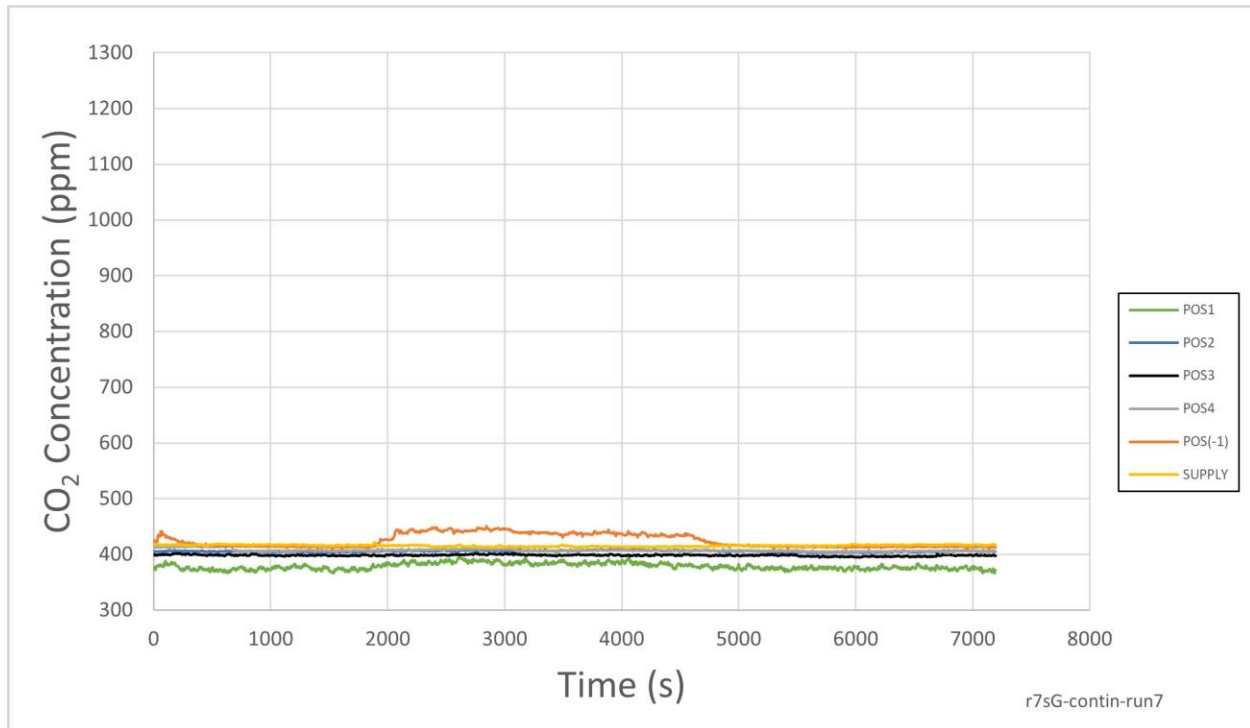
Appendix C C.4: Row 7 Seat G – Continuous – Run 4



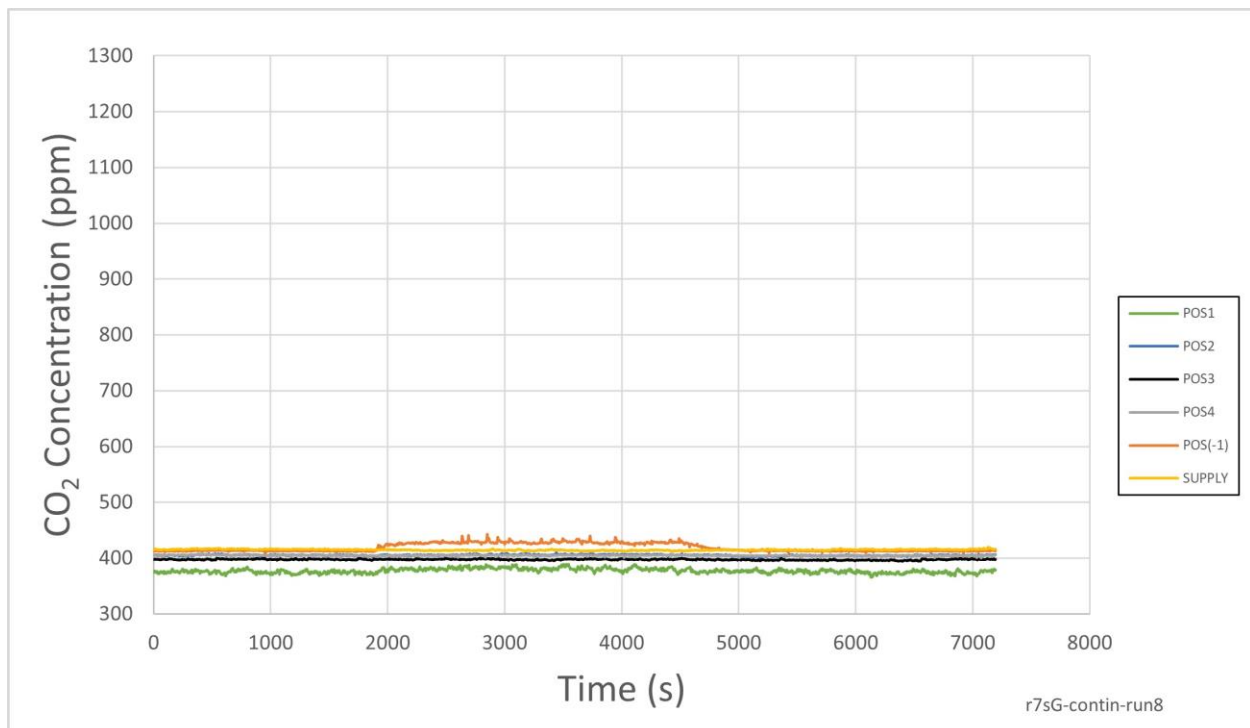
Appendix C C.5: Row 7 Seat G – Continuous – Run 5



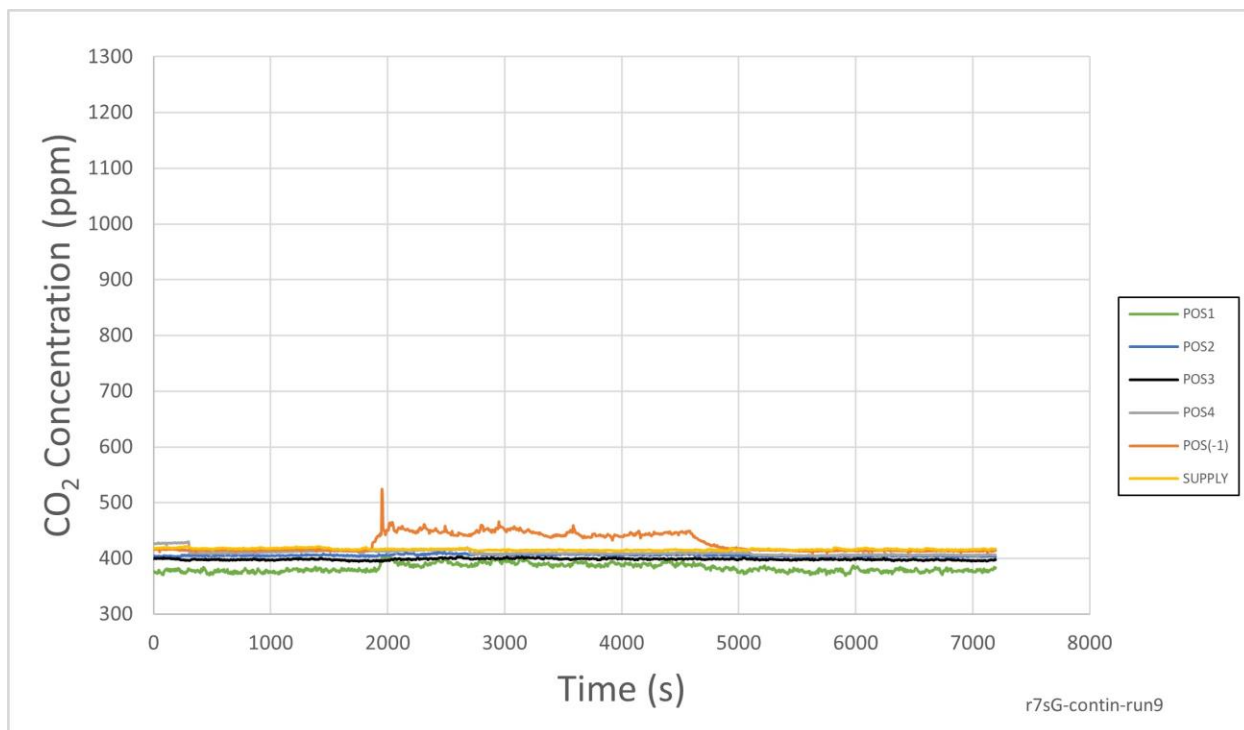
Appendix C C.6: Row 7 Seat G – Continuous – Run 6



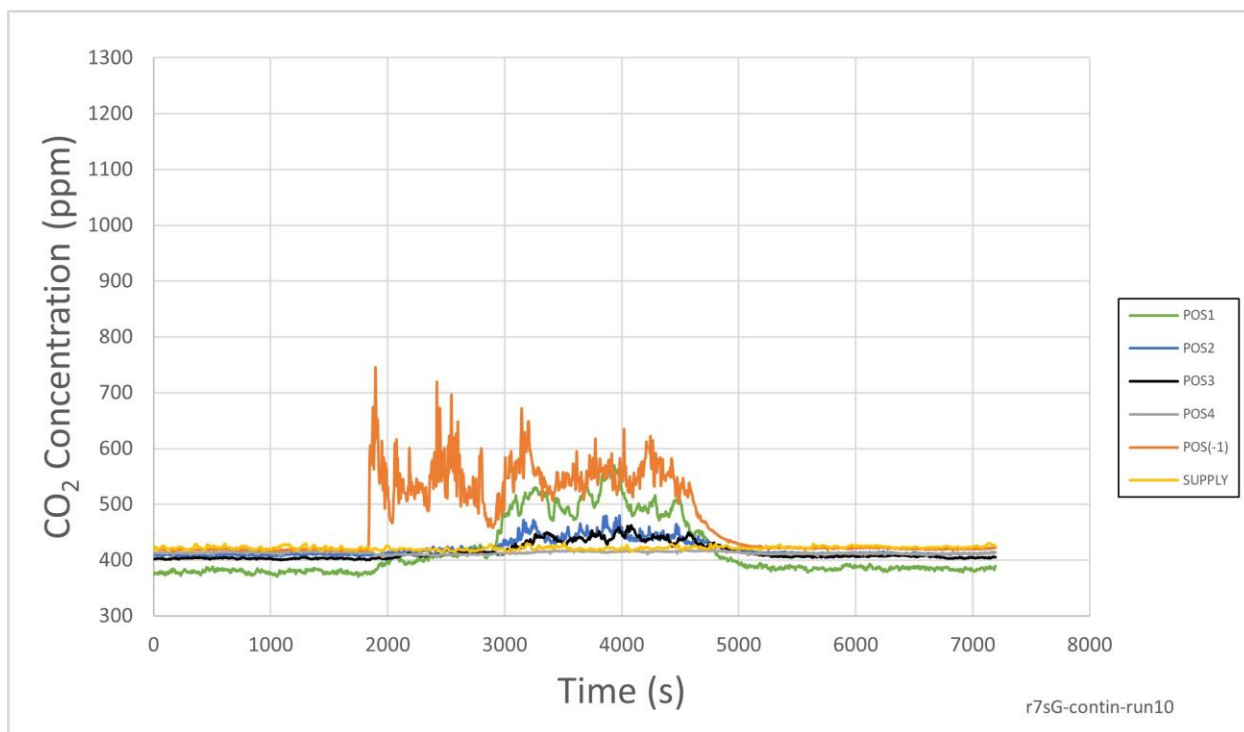
Appendix C C.7: Row 7 Seat G – Continuous – Run 7



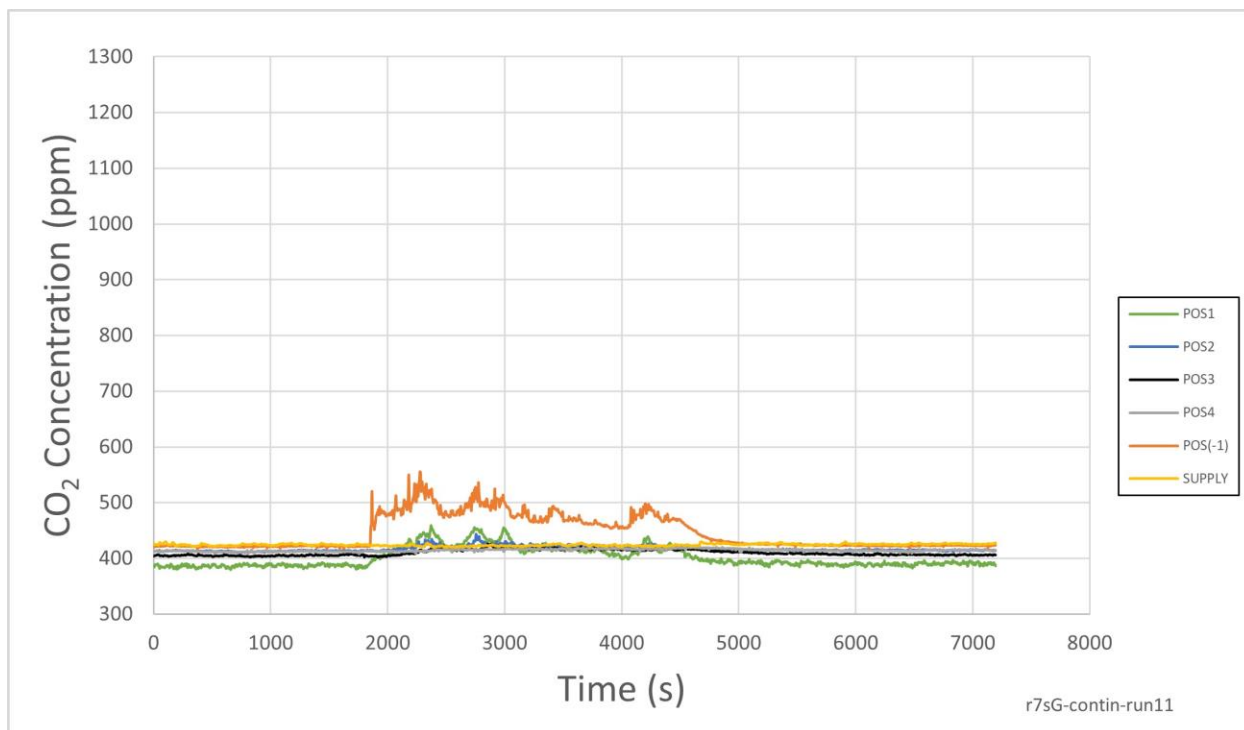
Appendix C C.8: Row 7 Seat G – Continuous – Run 8



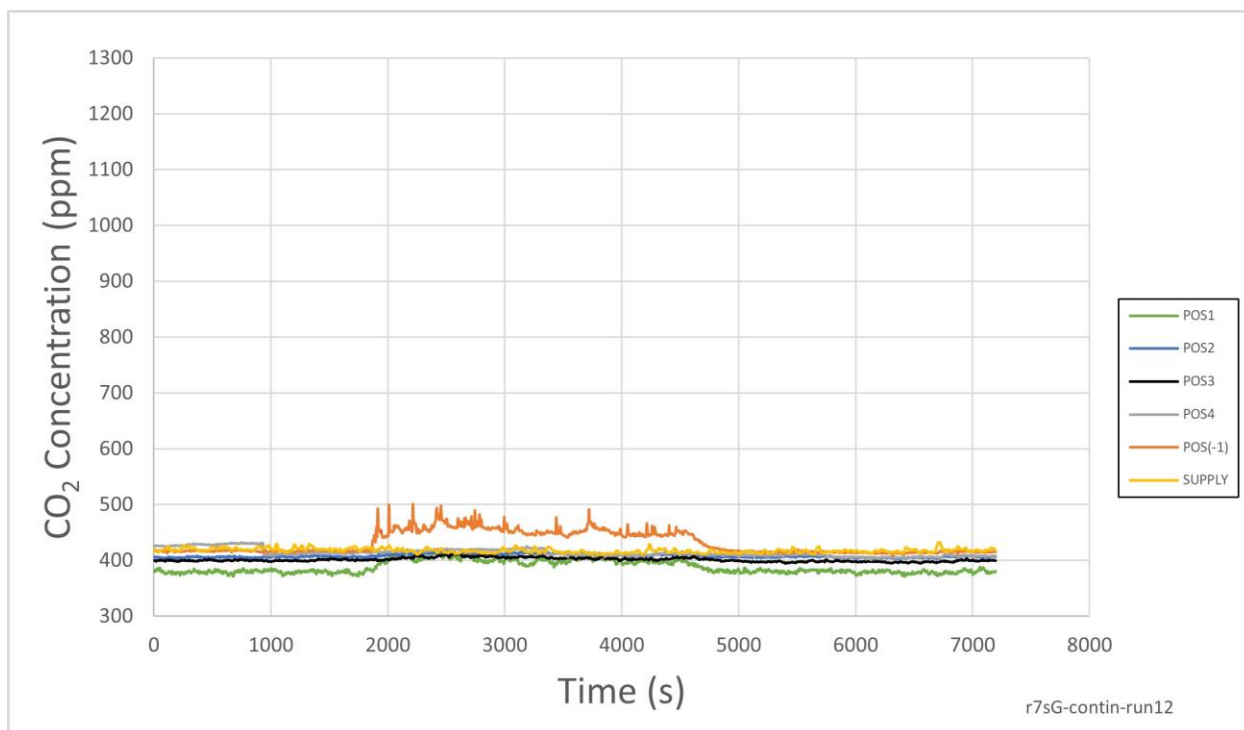
Appendix C C.9: Row 7 Seat G – Continuous – Run 9



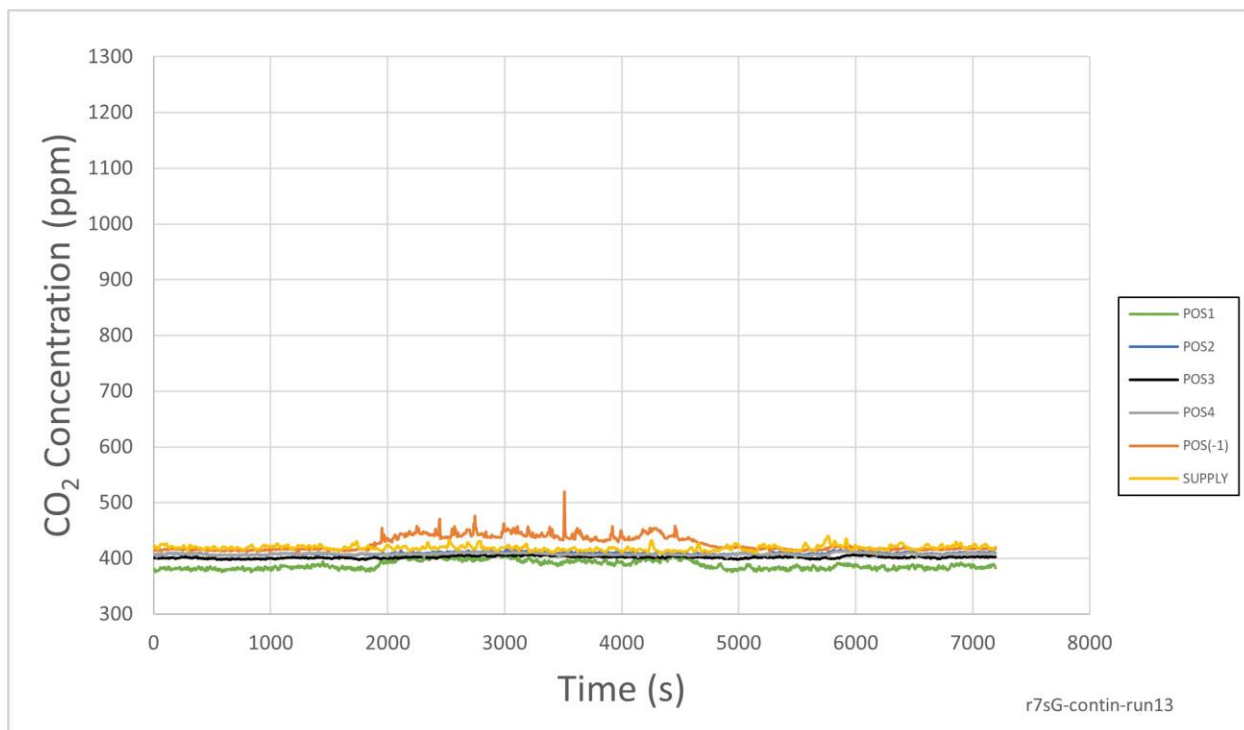
Appendix C C.10: Row 7 Seat G – Continuous – Run 10



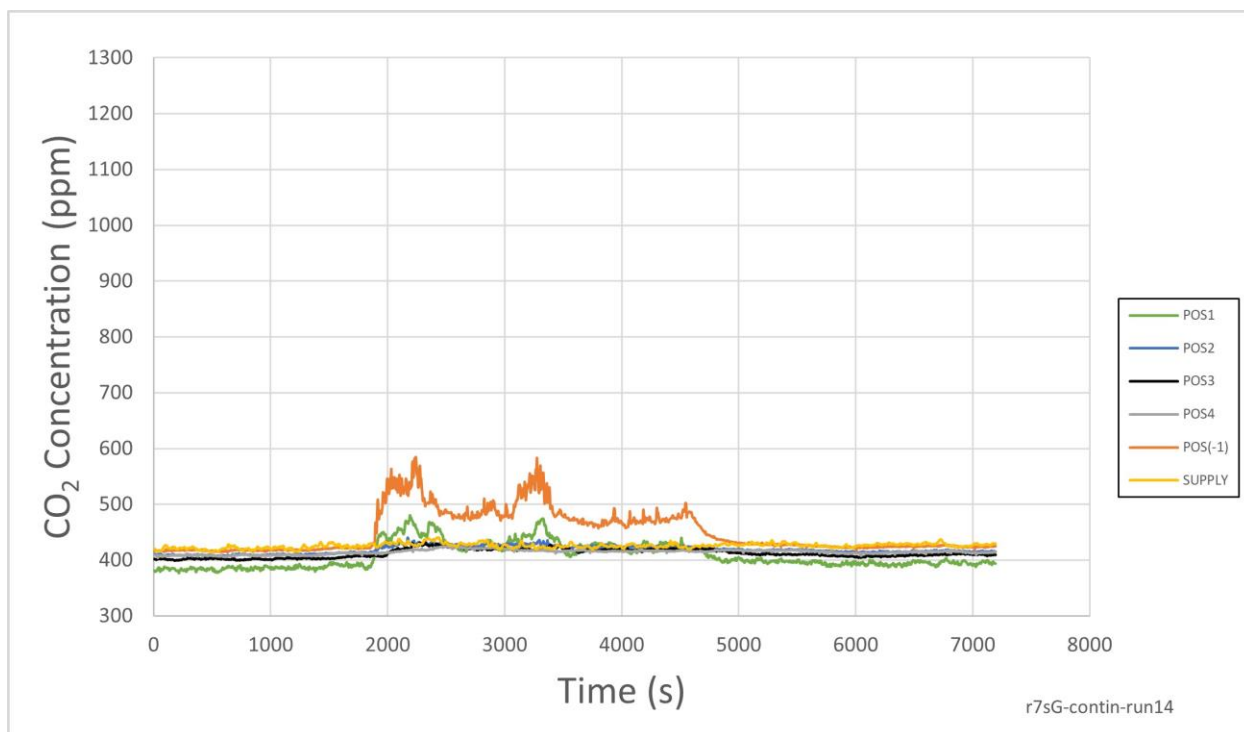
Appendix C C.11: Row 7 Seat G – Continuous – Run 11



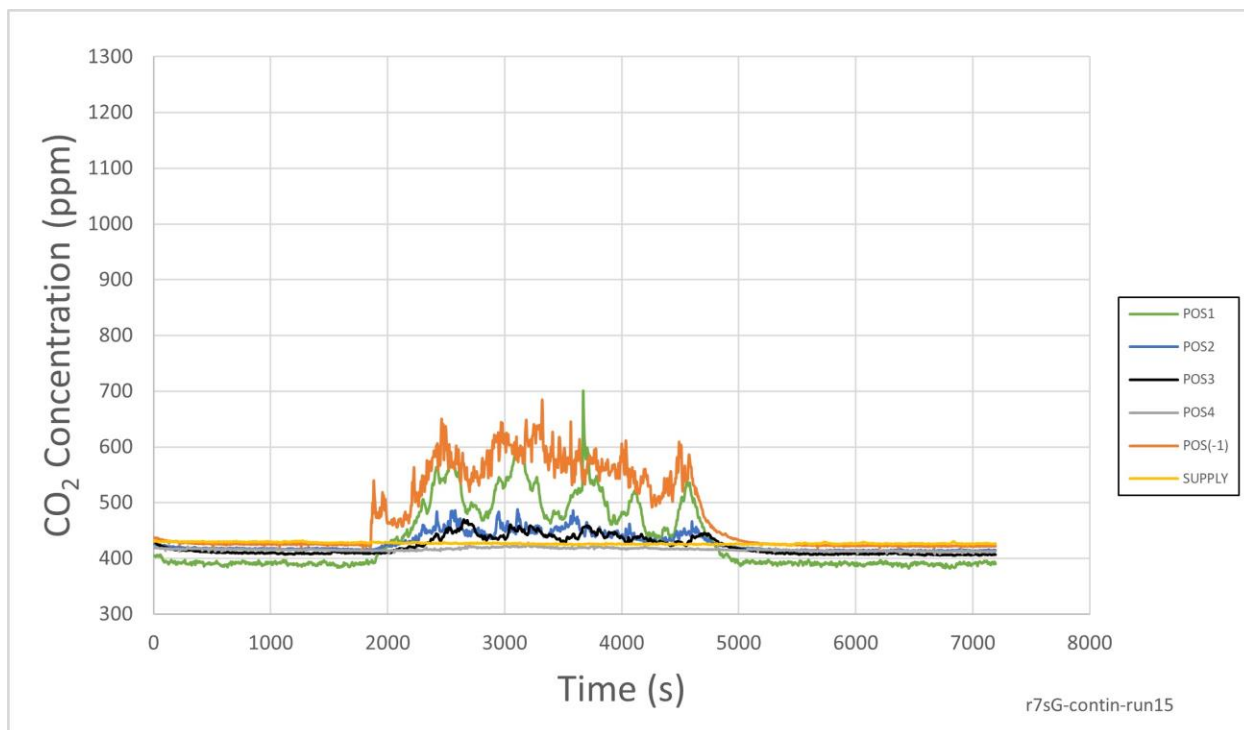
Appendix C C.12: Row 7 Seat G – Continuous – Run 12



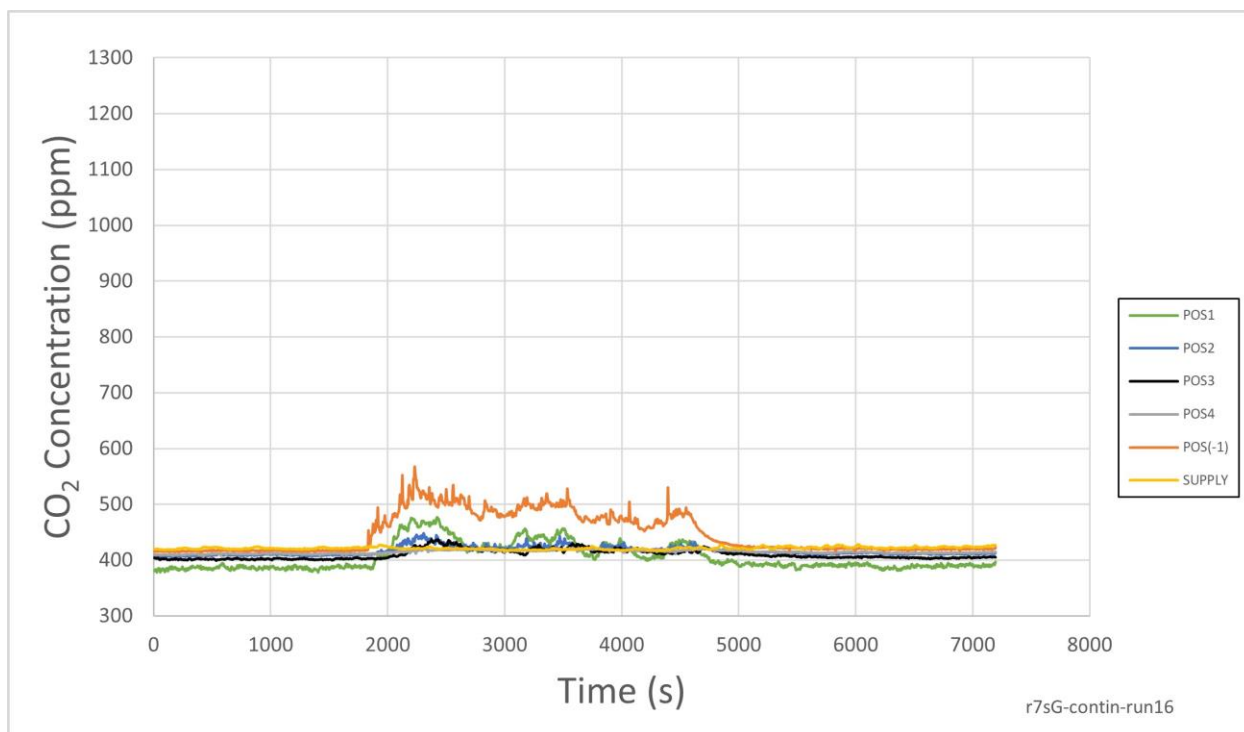
Appendix C C.13: Row 7 Seat G – Continuous – Run 13



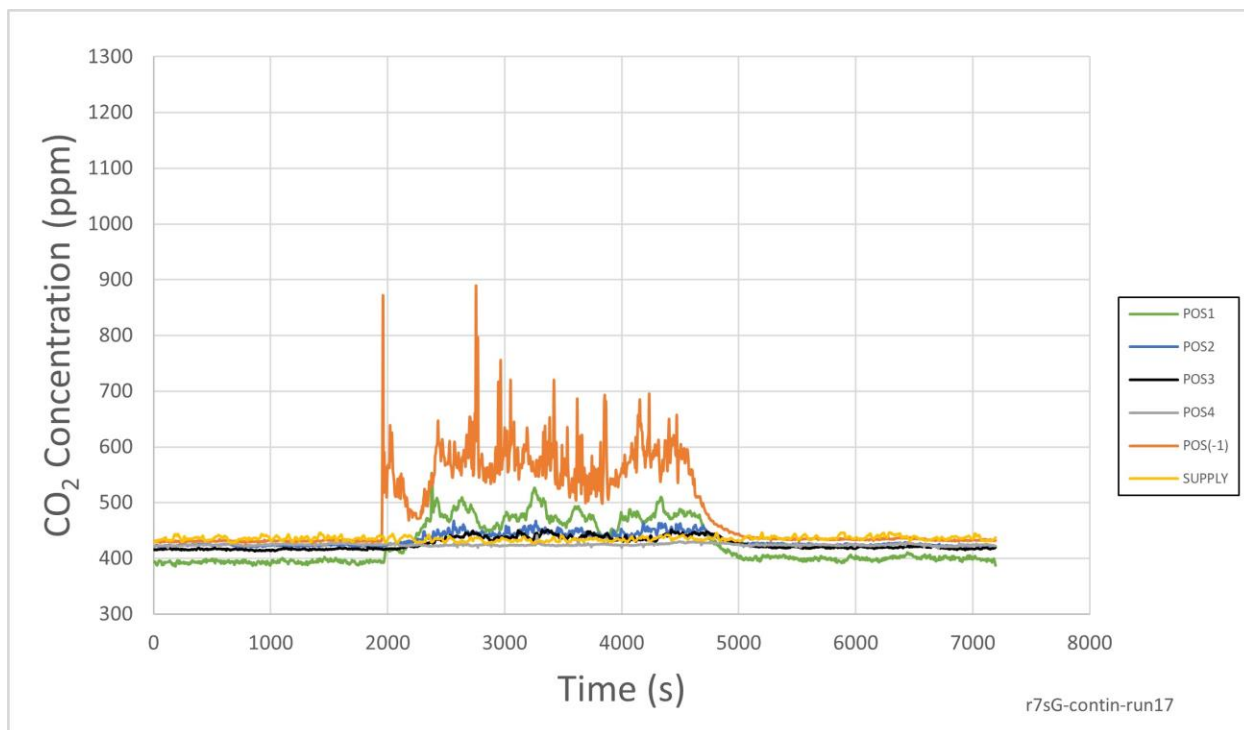
Appendix C C.14: Row 7 Seat G – Continuous – Run 14



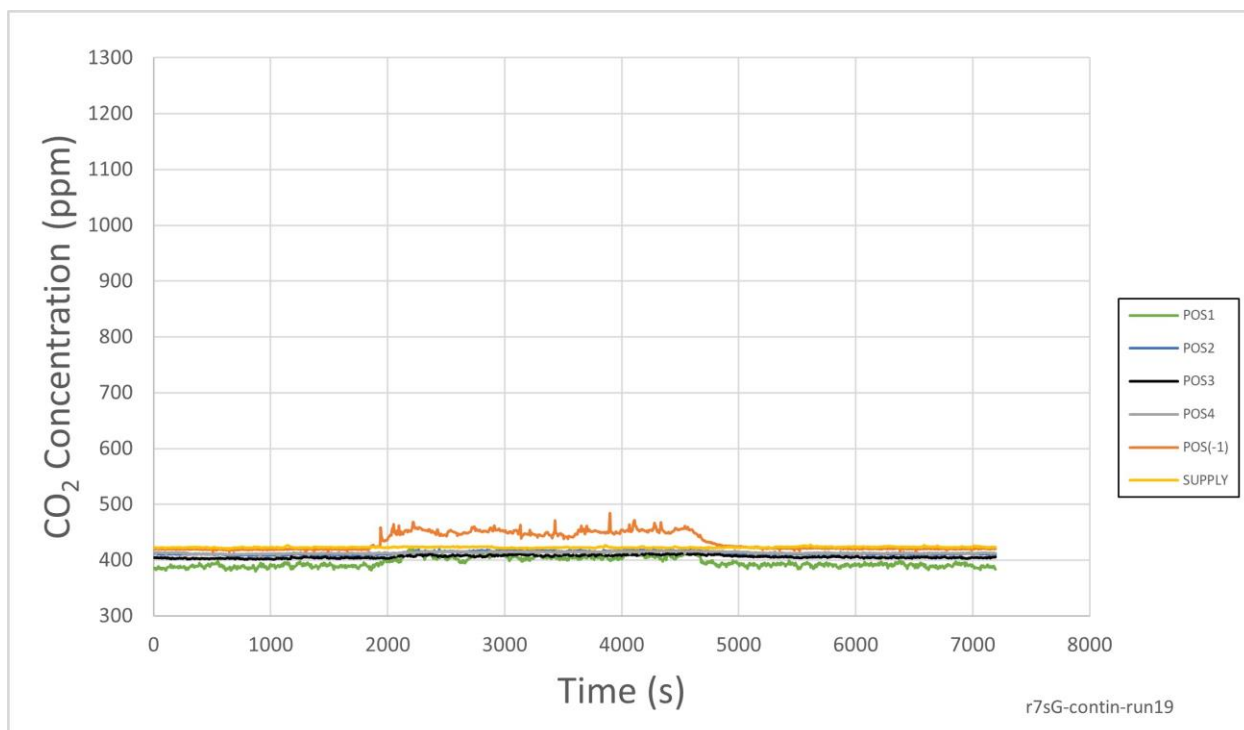
Appendix C C.15: Row 7 Seat G – Continuous – Run 15



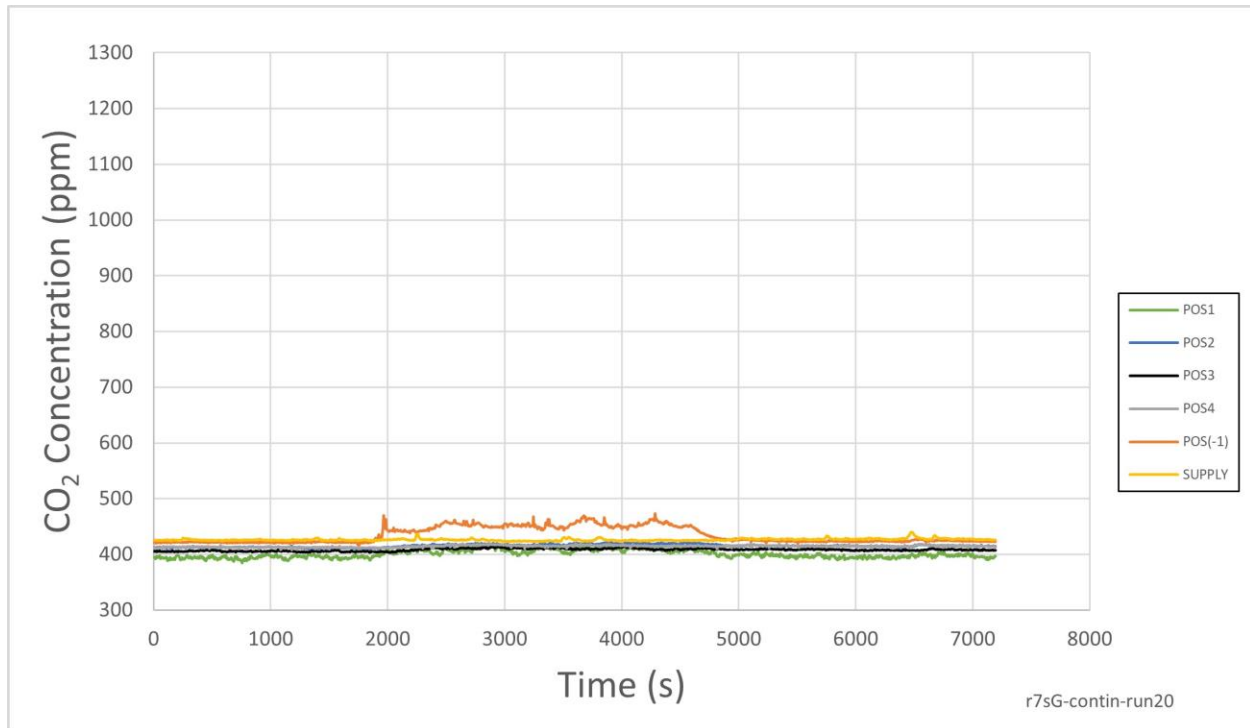
Appendix C C.16: Row 7 Seat G – Continuous – Run 16



Appendix C C.17: Row 7 Seat G – Continuous – Run 17

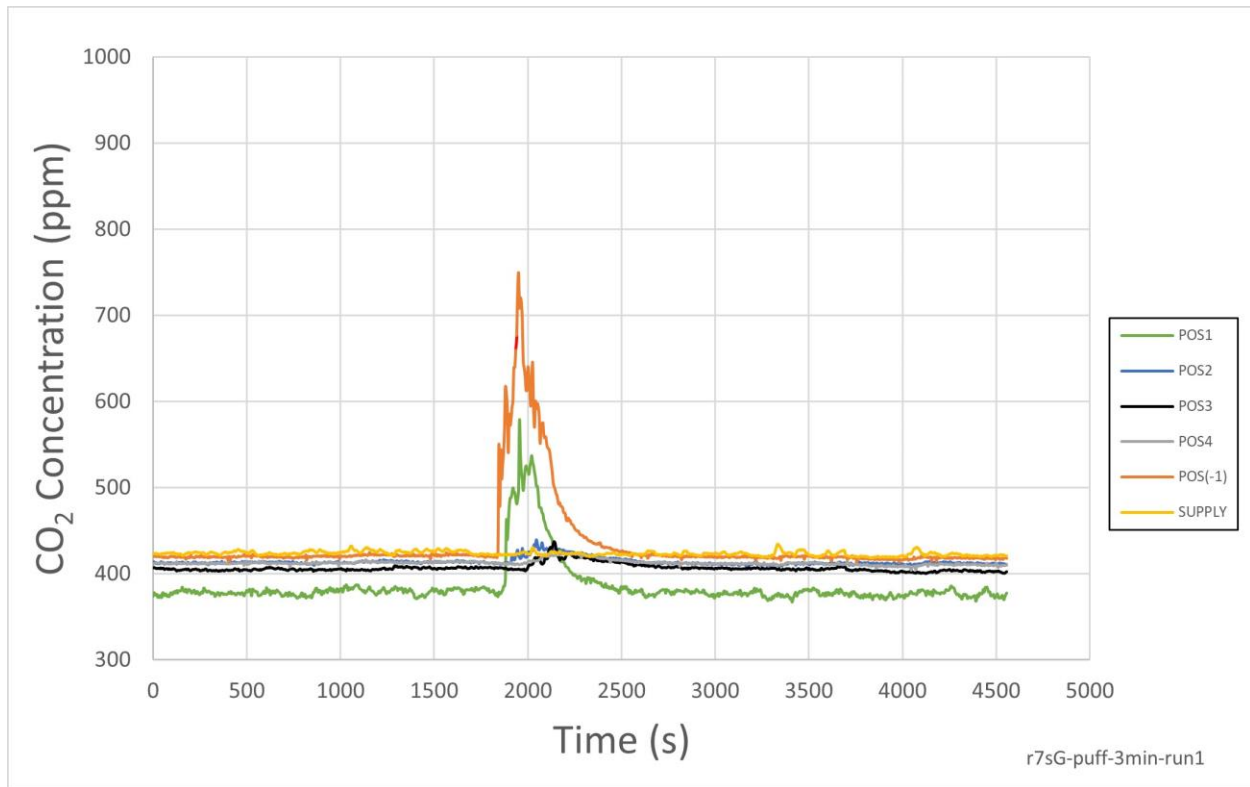


Appendix C C.18: Row 7 Seat G – Continuous – Run 18

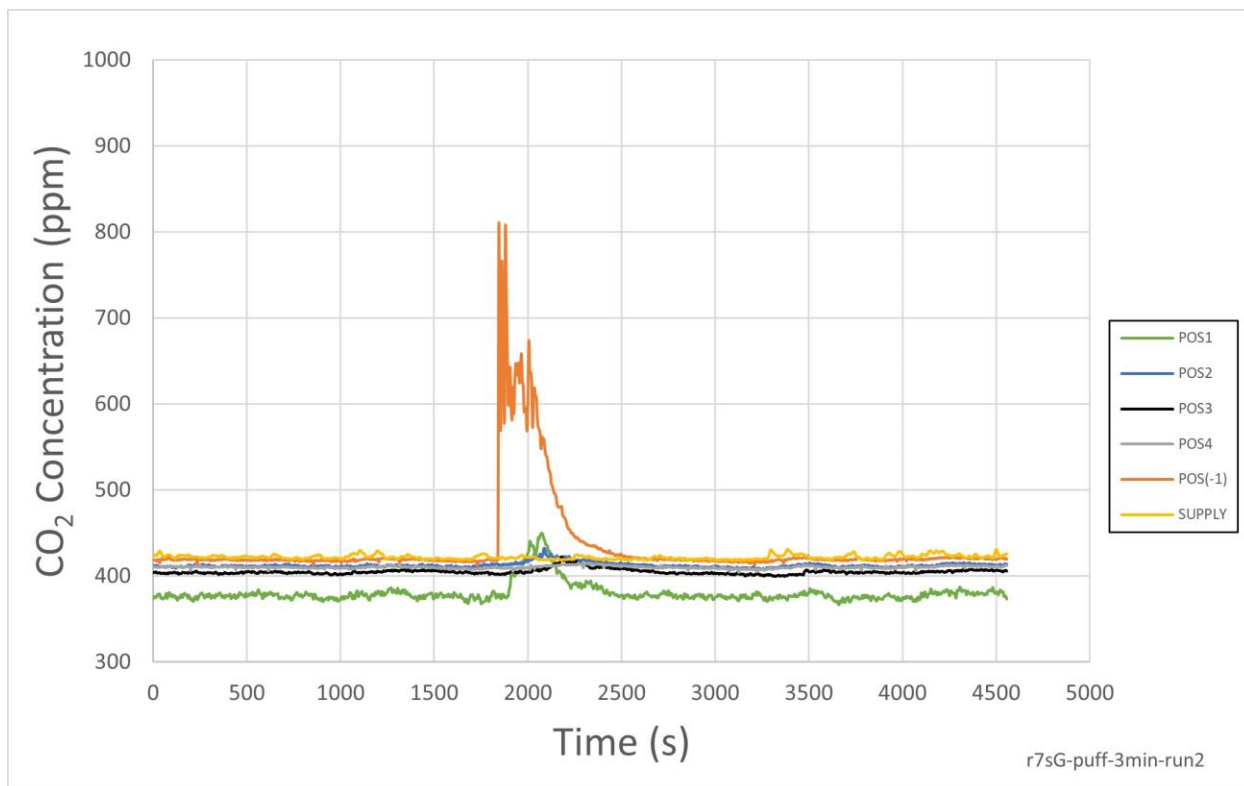


Appendix C C.19: Row 7 Seat G – Continuous – Run 19

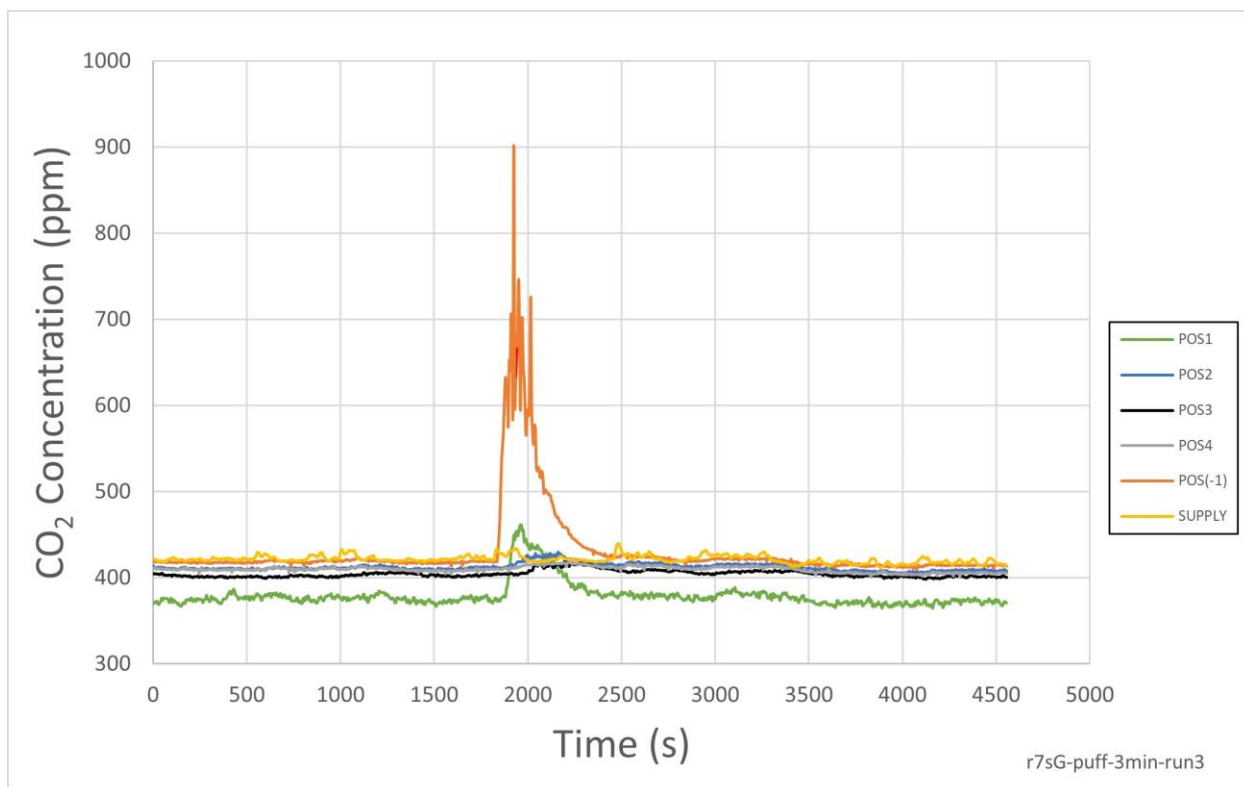
Appendix D - Row 7 Seat G – Puff Injection Responses



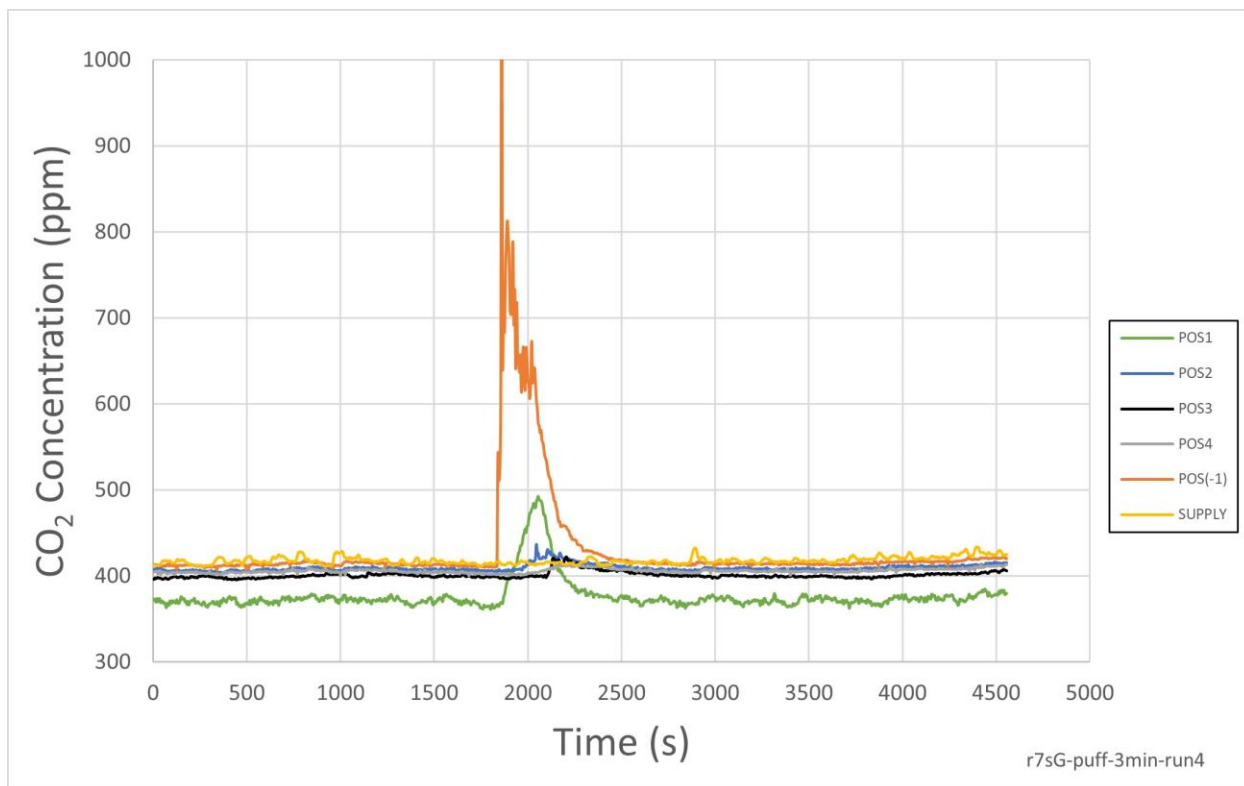
Appendix D D.1: Row 7 Seat G – 3-Minutes Puff – Run 1



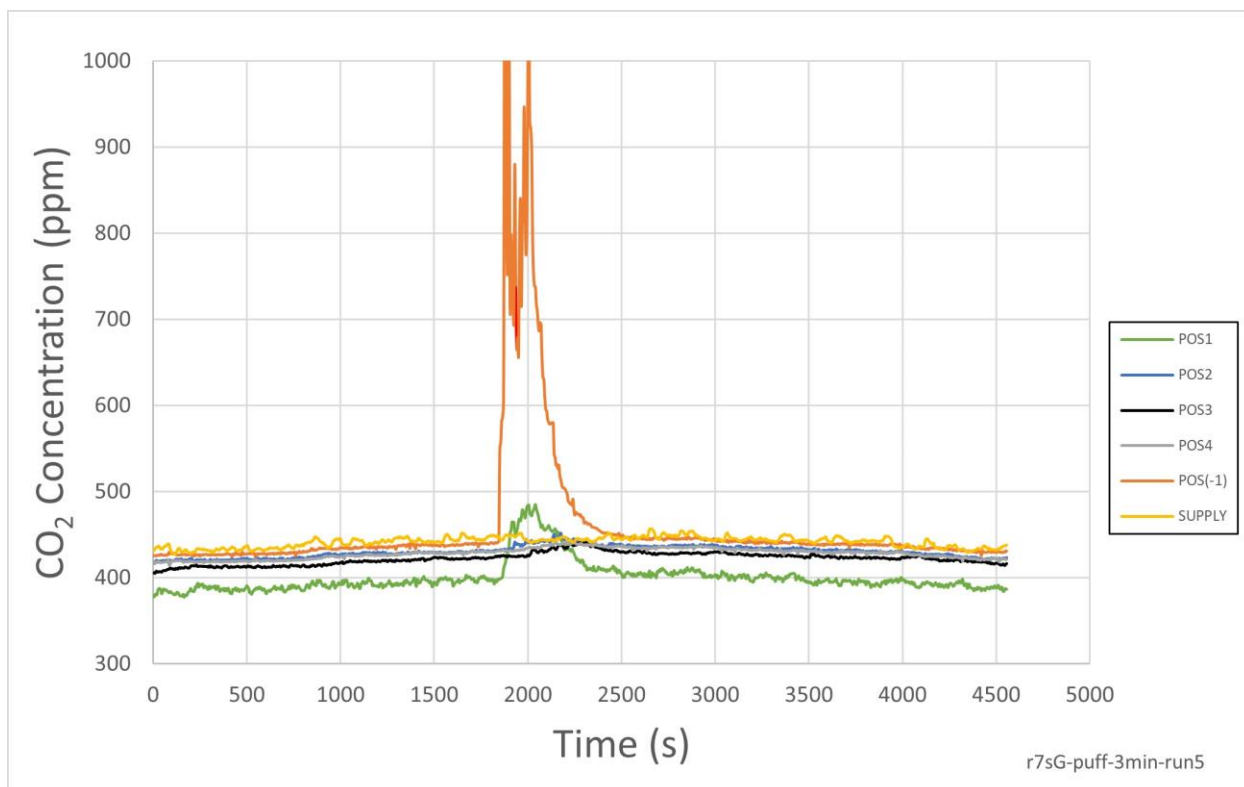
Appendix D D.2: Row 7 Seat G – 3-Minutes Puff – Run 2



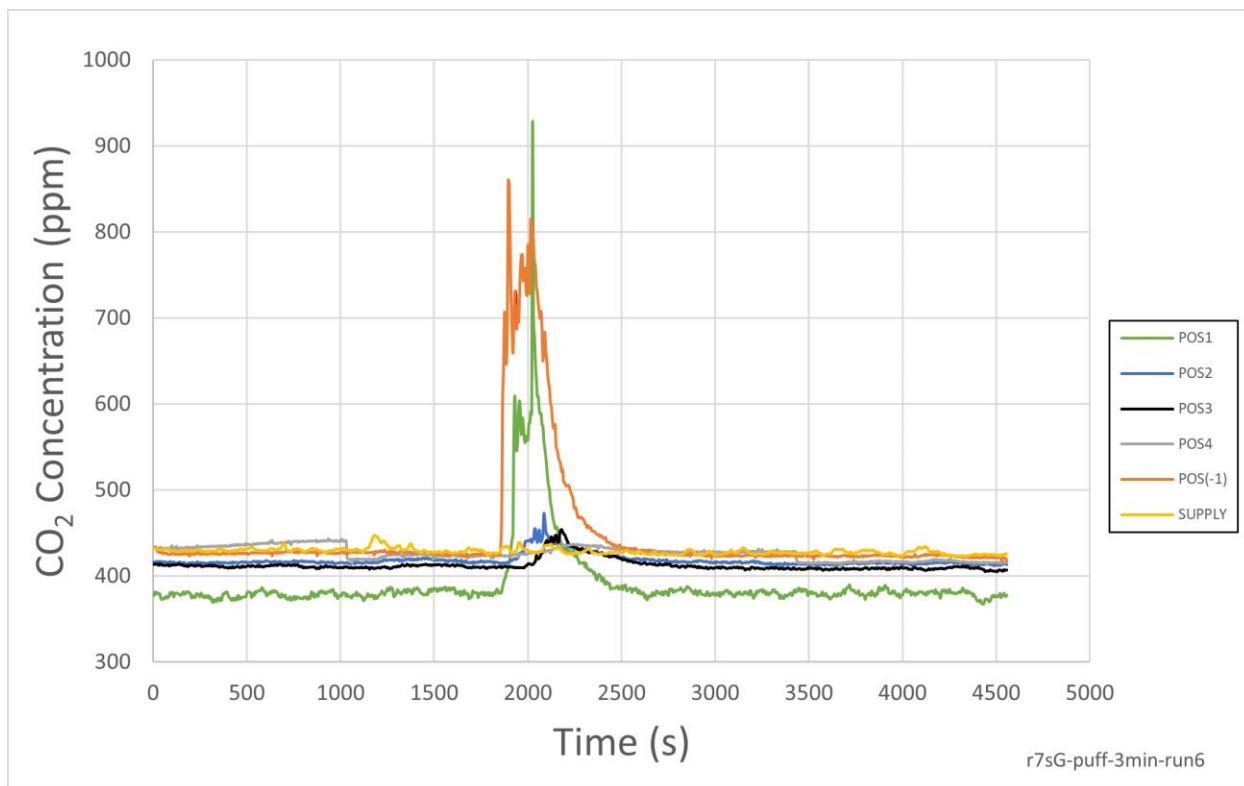
Appendix D D.3: Row 7 Seat G – 3-Minutes Puff – Run 3



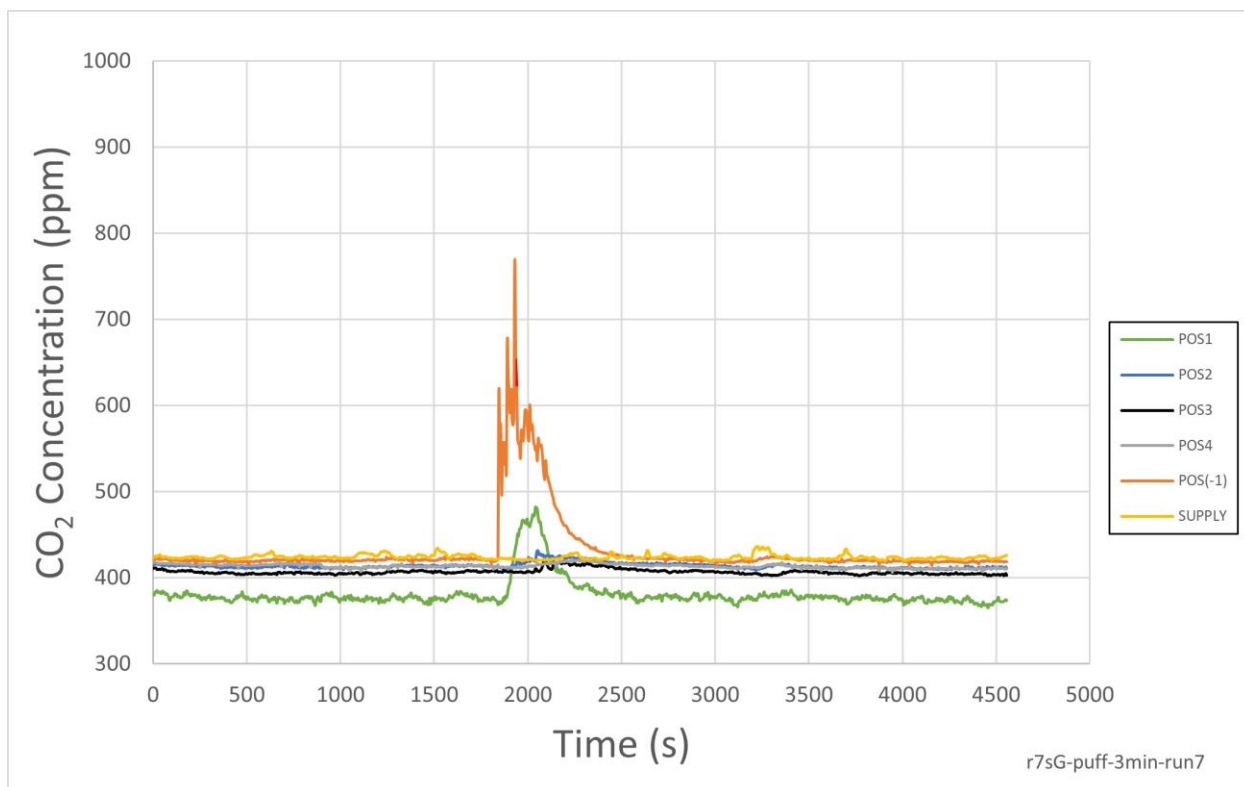
Appendix D D.4: Row 7 Seat G – 3-Minutes Puff – Run 4



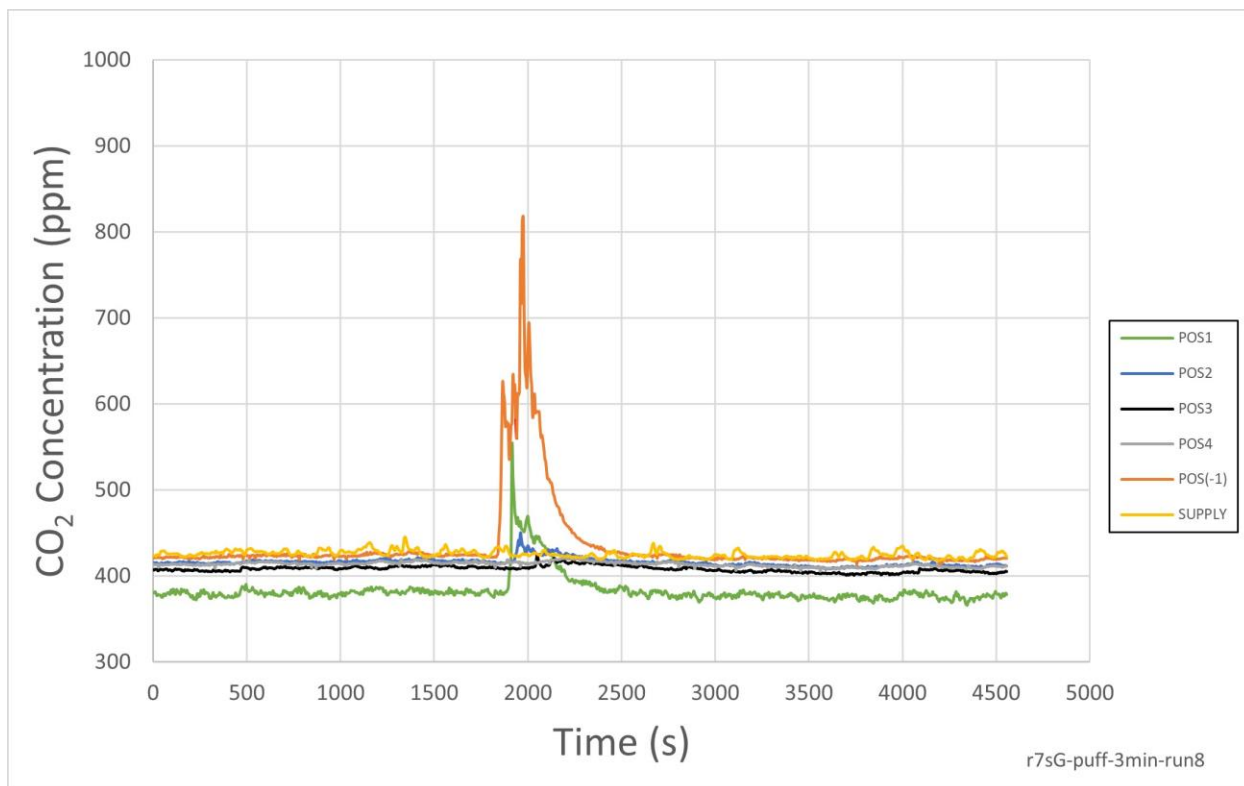
Appendix D D.5: Row 7 Seat G – 3-Minutes Puff – Run 5



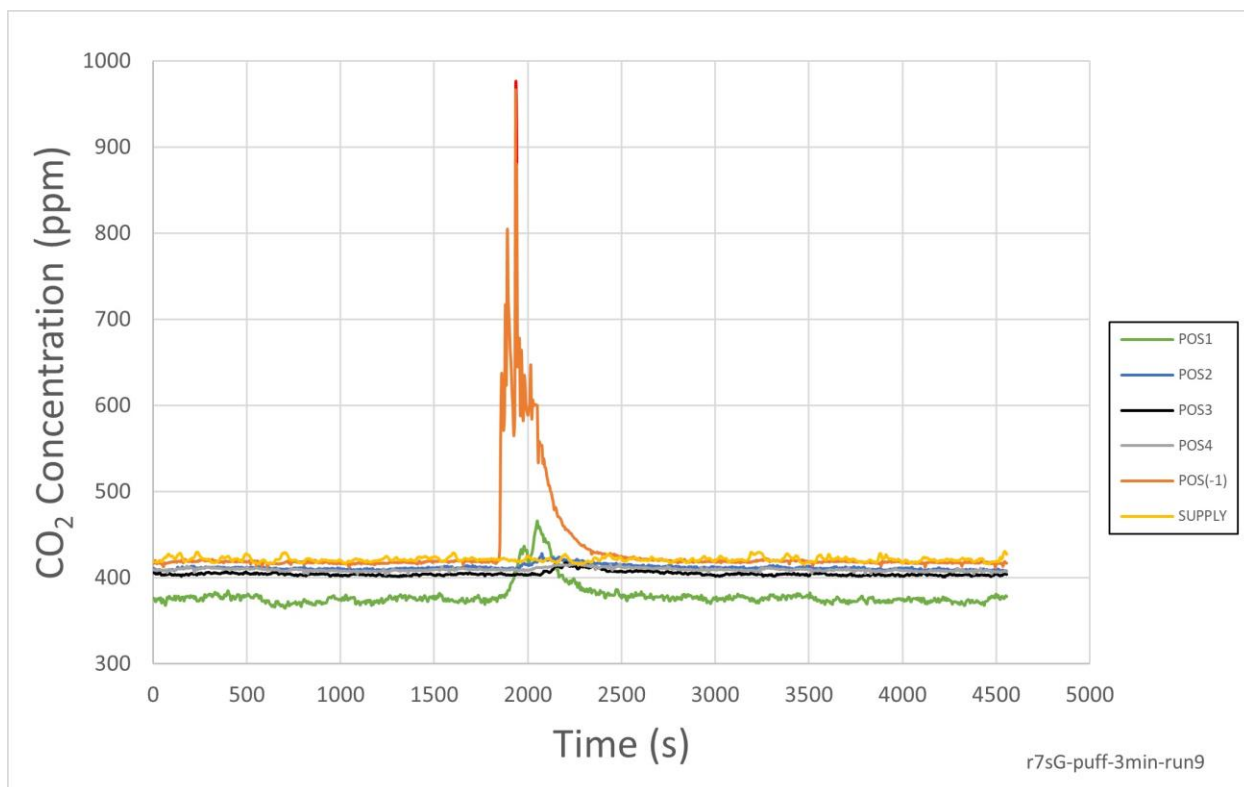
Appendix D D.6: Row 7 Seat G – 3-Minutes Puff – Run 6



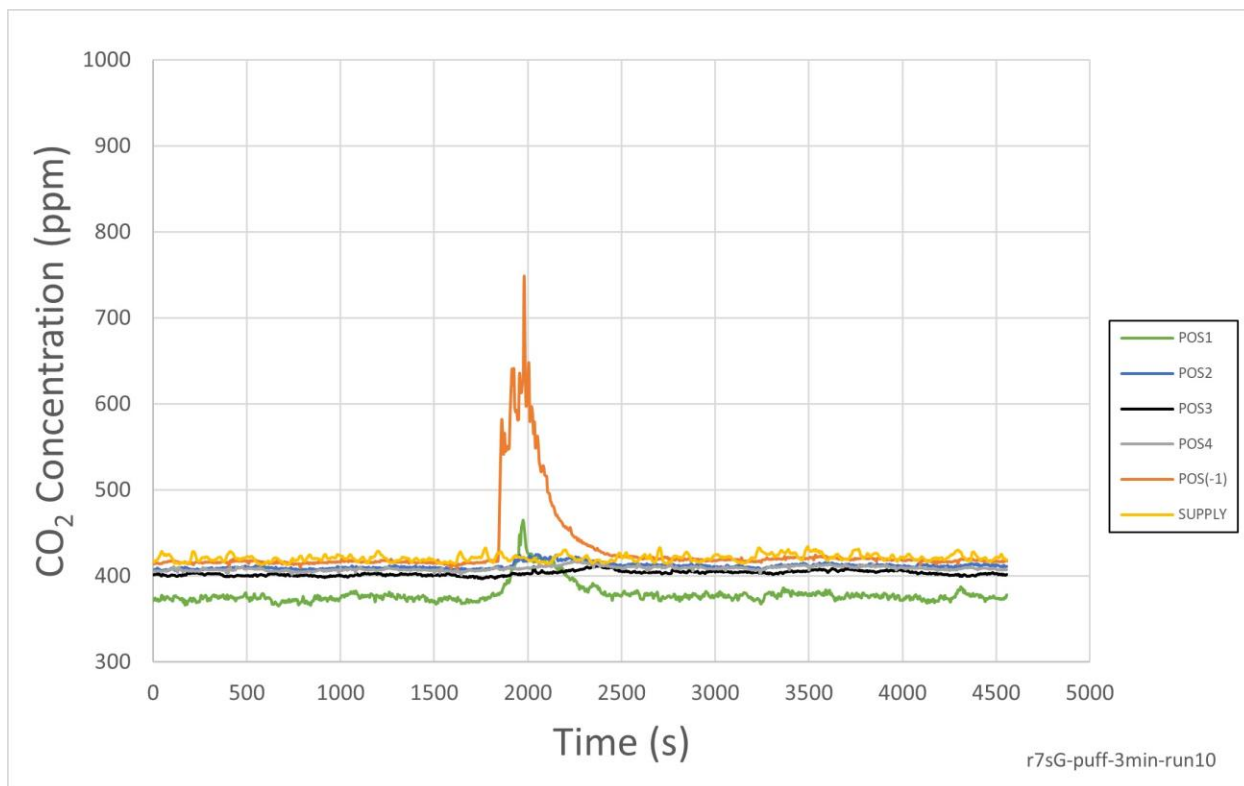
Appendix D D.7: Row 7 Seat G – 3-Minutes Puff – Run 7



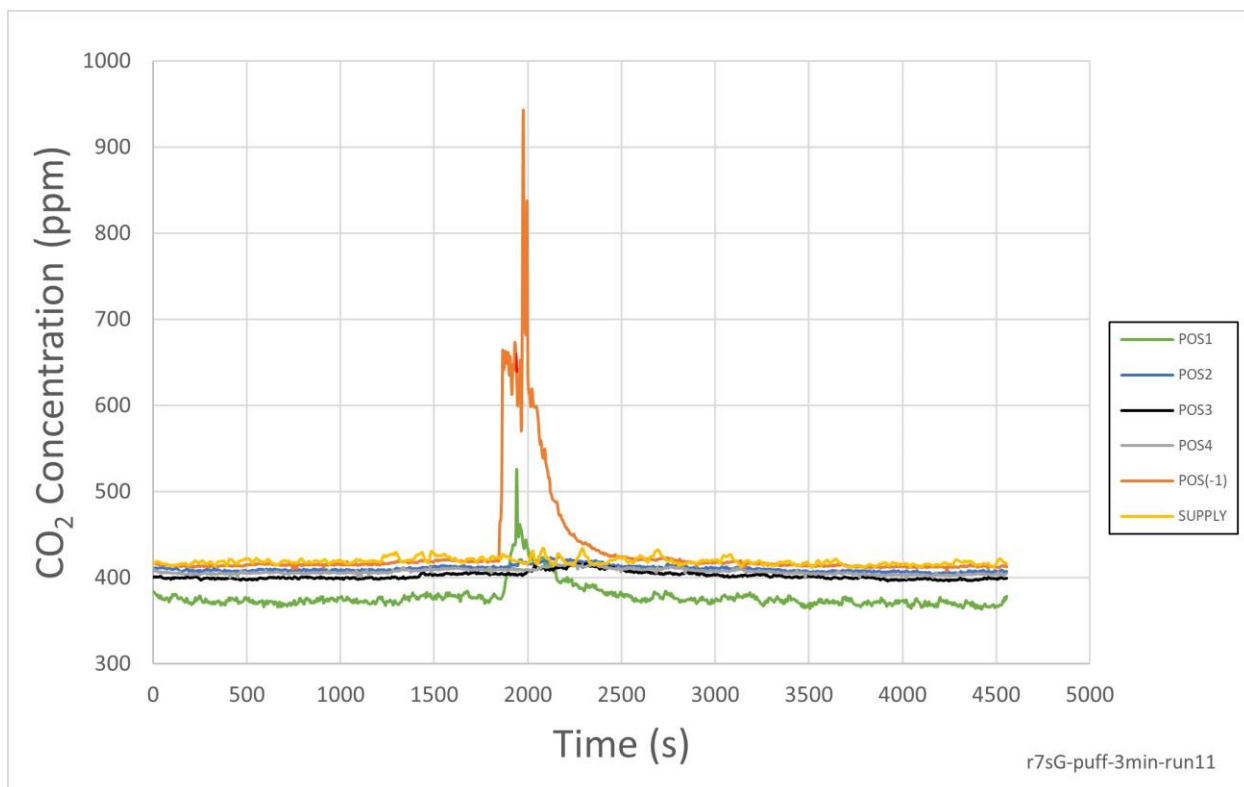
Appendix D D.8: Row 7 Seat G – 3-Minutes Puff – Run 8



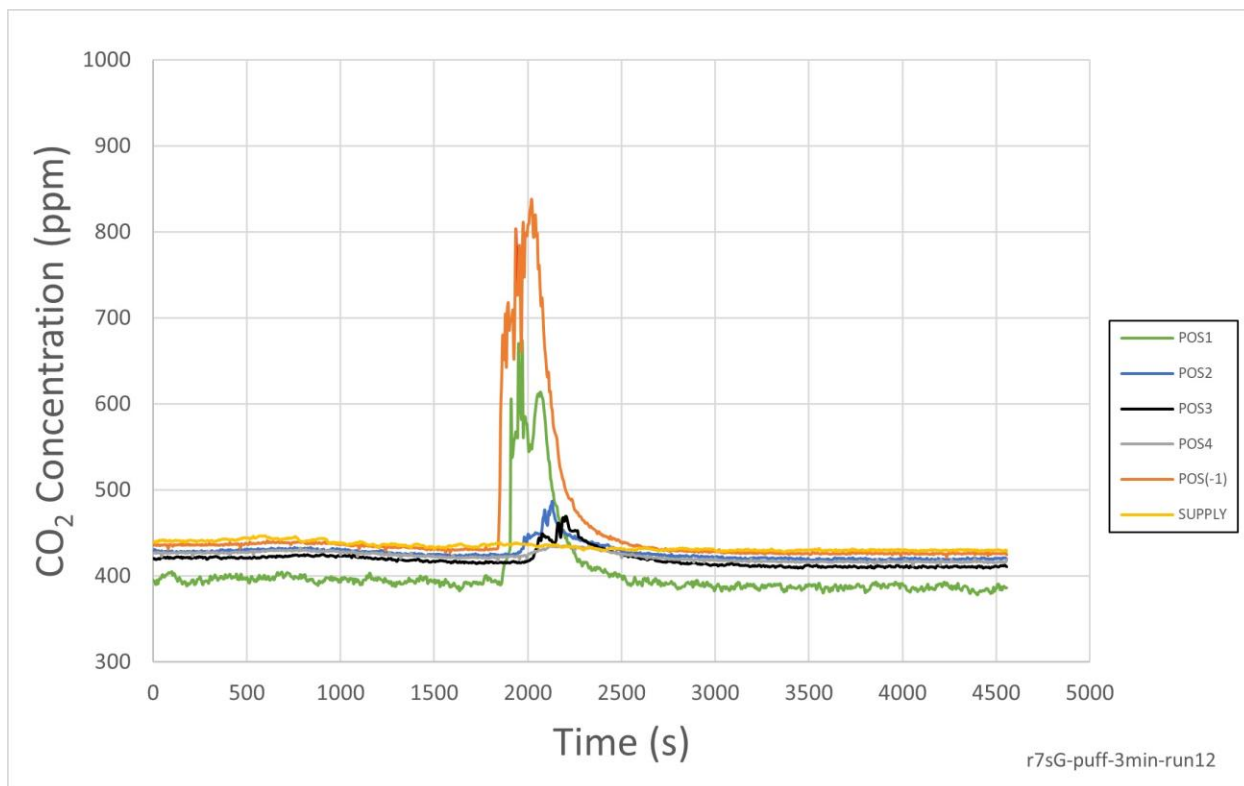
Appendix D D.9: Row 7 Seat G – 3-Minutes Puff – Run 9



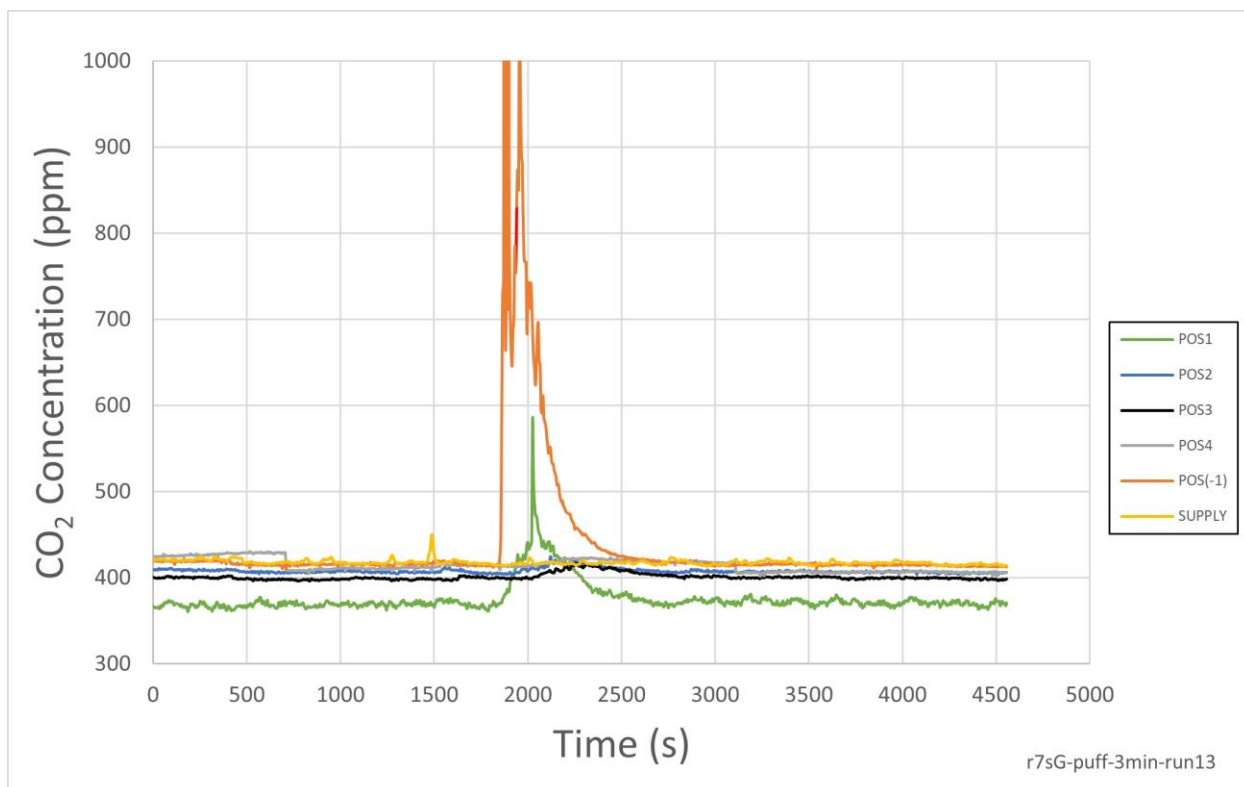
Appendix D D.10: Row 7 Seat G – 3-Minutes Puff – Run 10



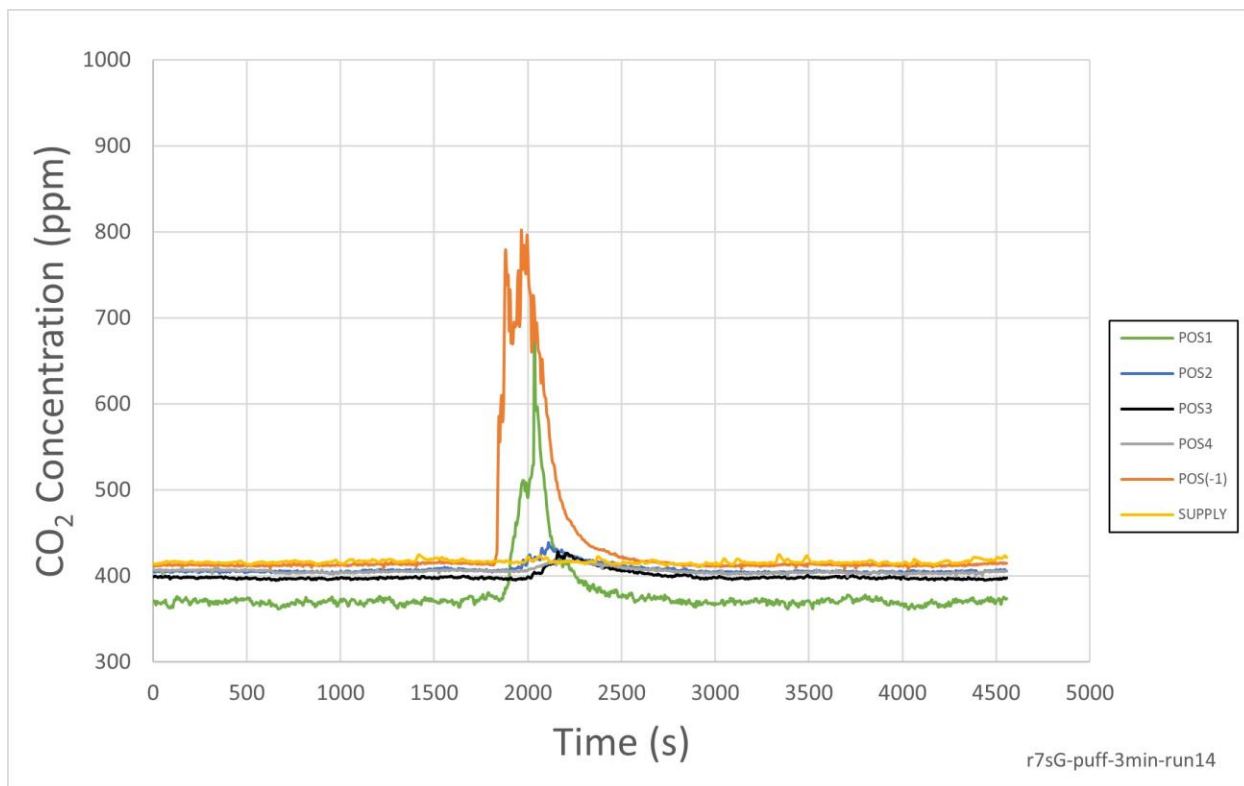
Appendix D D.11: Row 7 Seat G – 3-Minutes Puff – Run 11



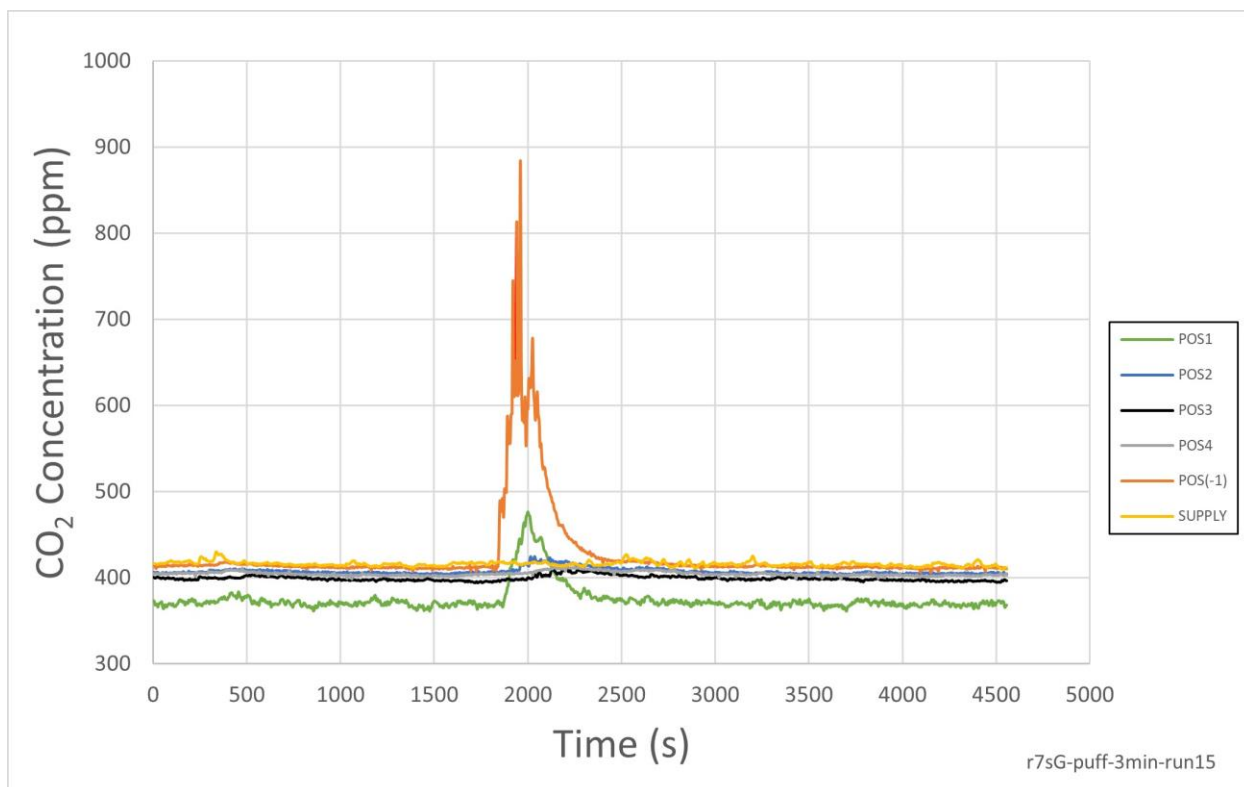
Appendix D D.12: Row 7 Seat G – 3-Minutes Puff – Run 12



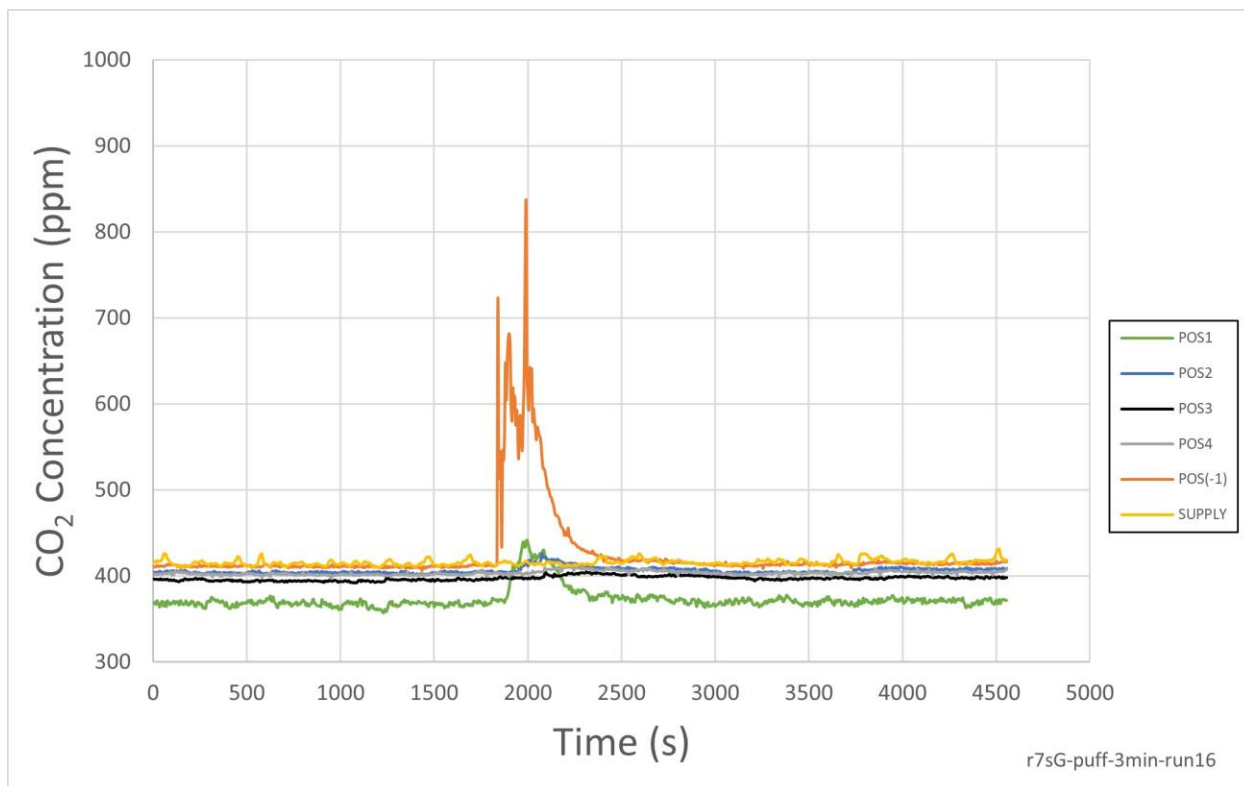
Appendix D D.13: Row 7 Seat G – 3-Minutes Puff – Run 13



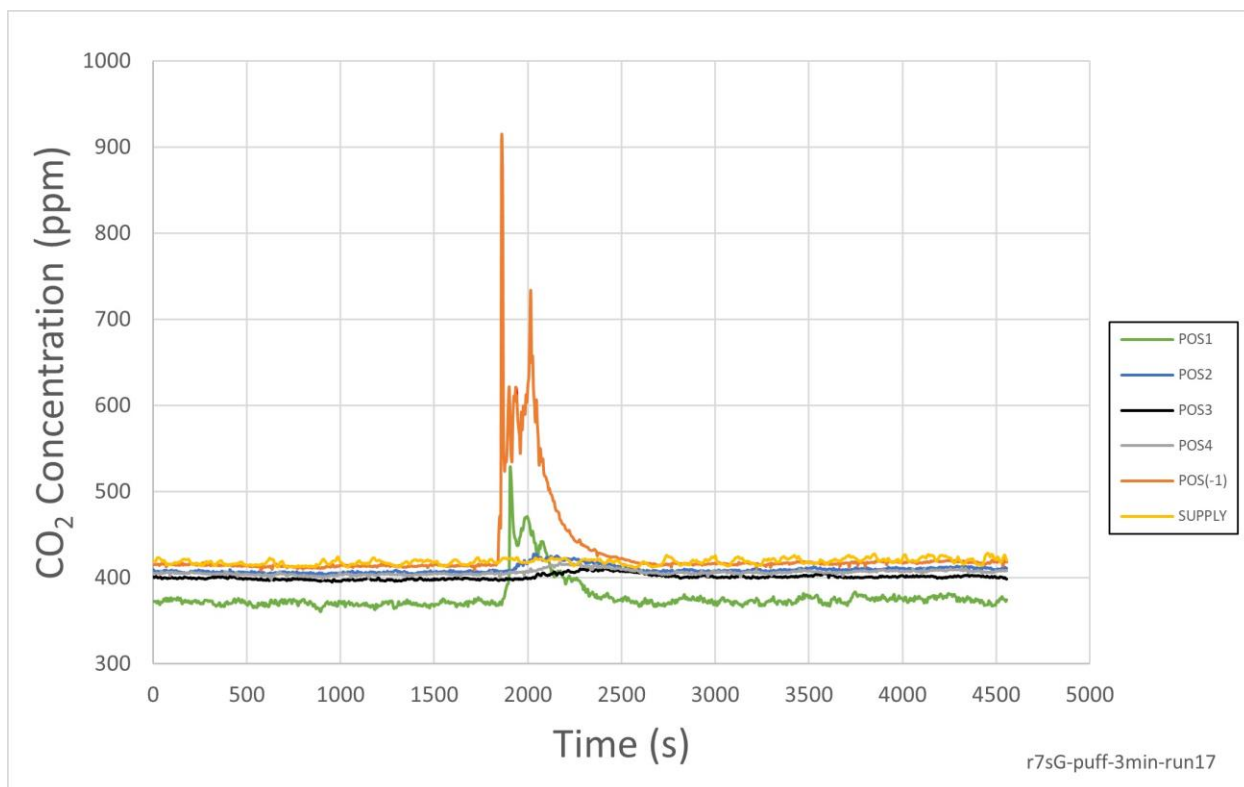
Appendix D D.14: Row 7 Seat G – 3-Minutes Puff – Run 14



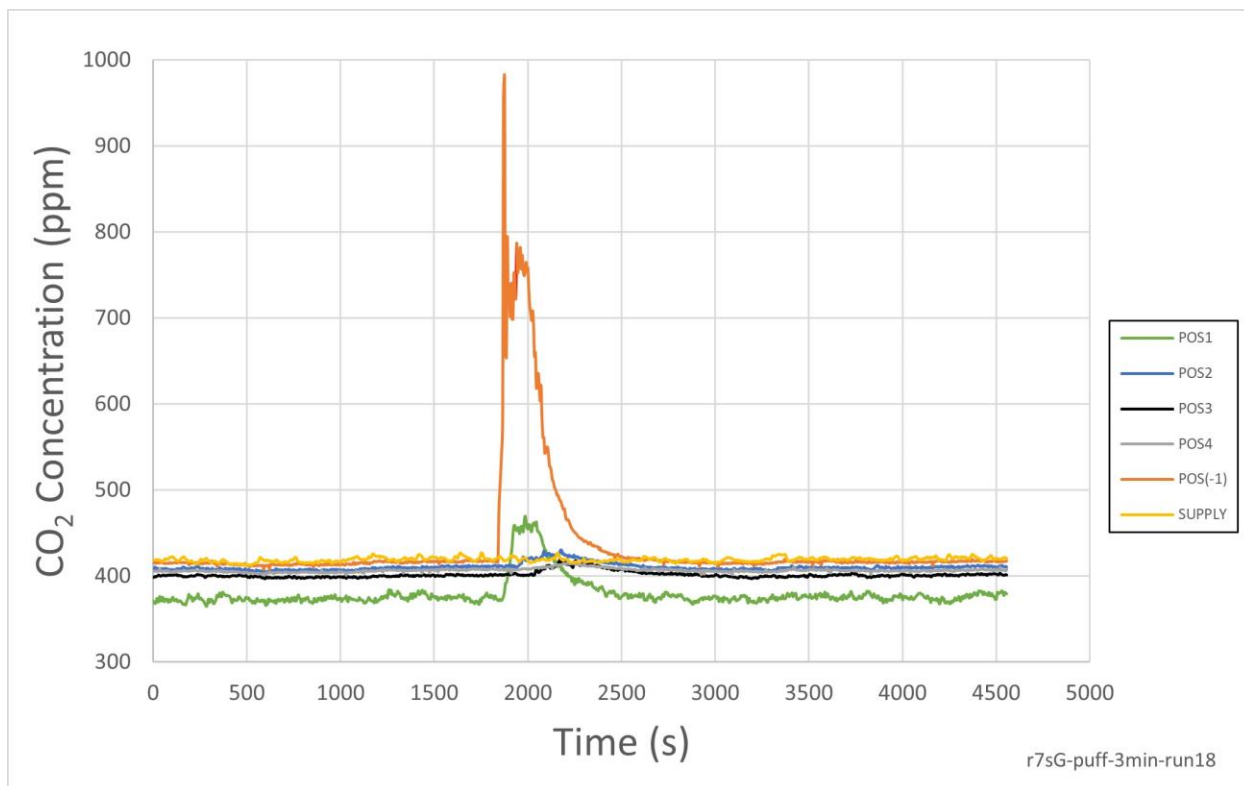
Appendix D D.15: Row 7 Seat G – 3-Minutes Puff – Run 15



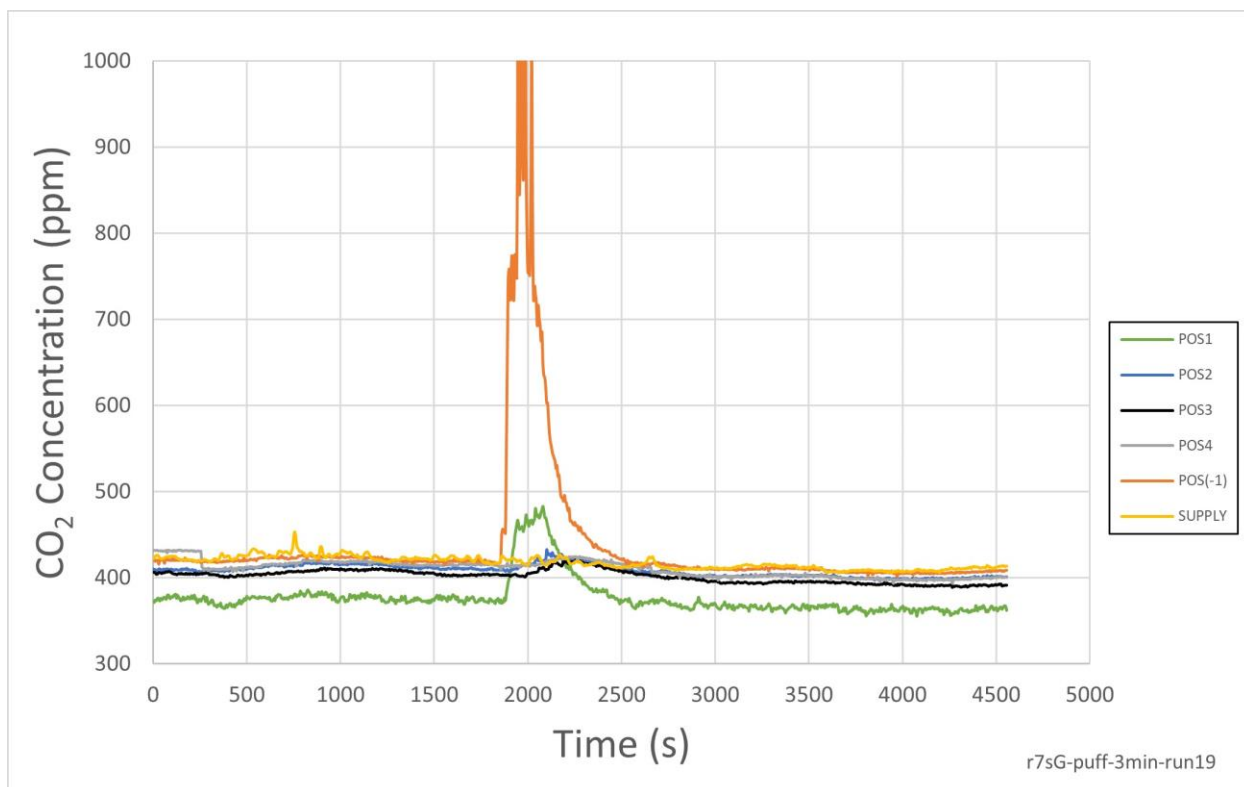
Appendix D D.16: Row 7 Seat G – 3-Minutes Puff – Run 16



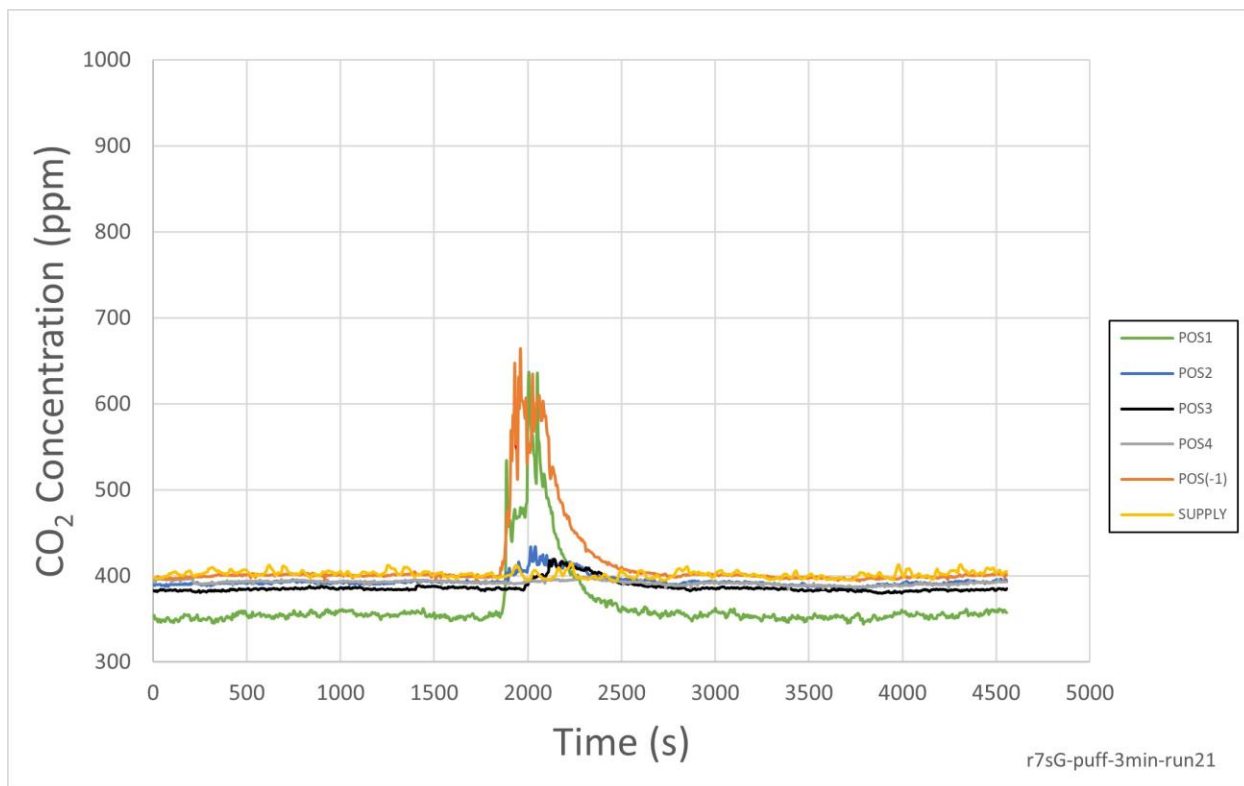
Appendix D D.17: Row 7 Seat G – 3-Minutes Puff – Run 17



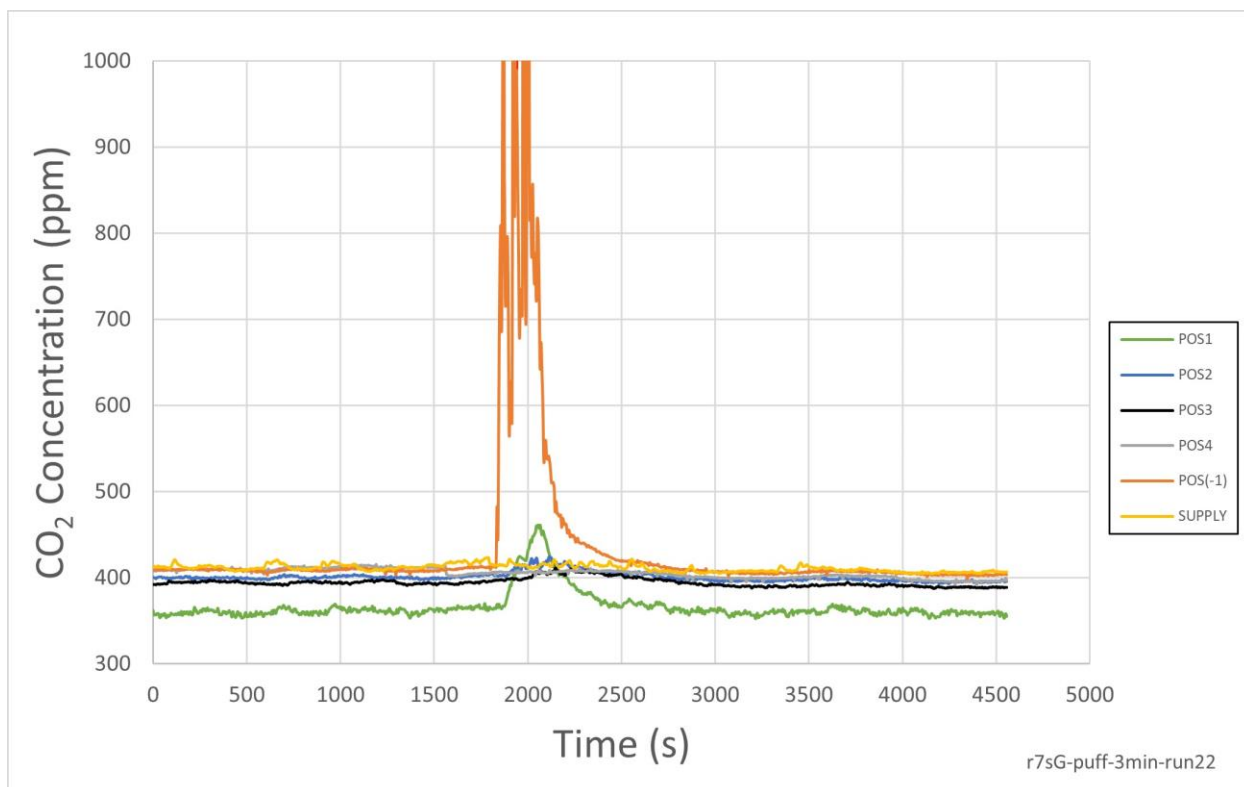
Appendix D D.18: Row 7 Seat G – 3-Minutes Puff – Run 18



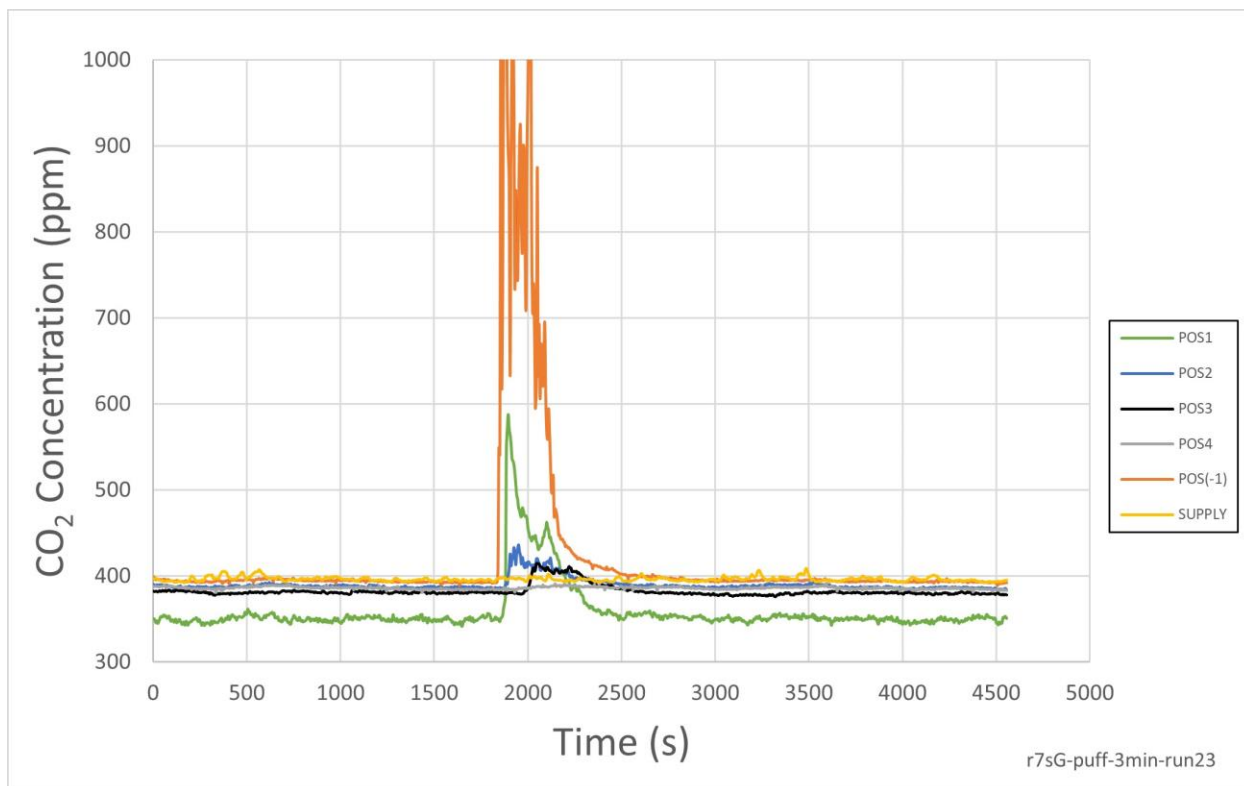
Appendix D D.19: Row 7 Seat G – 3-Minutes Puff – Run 19



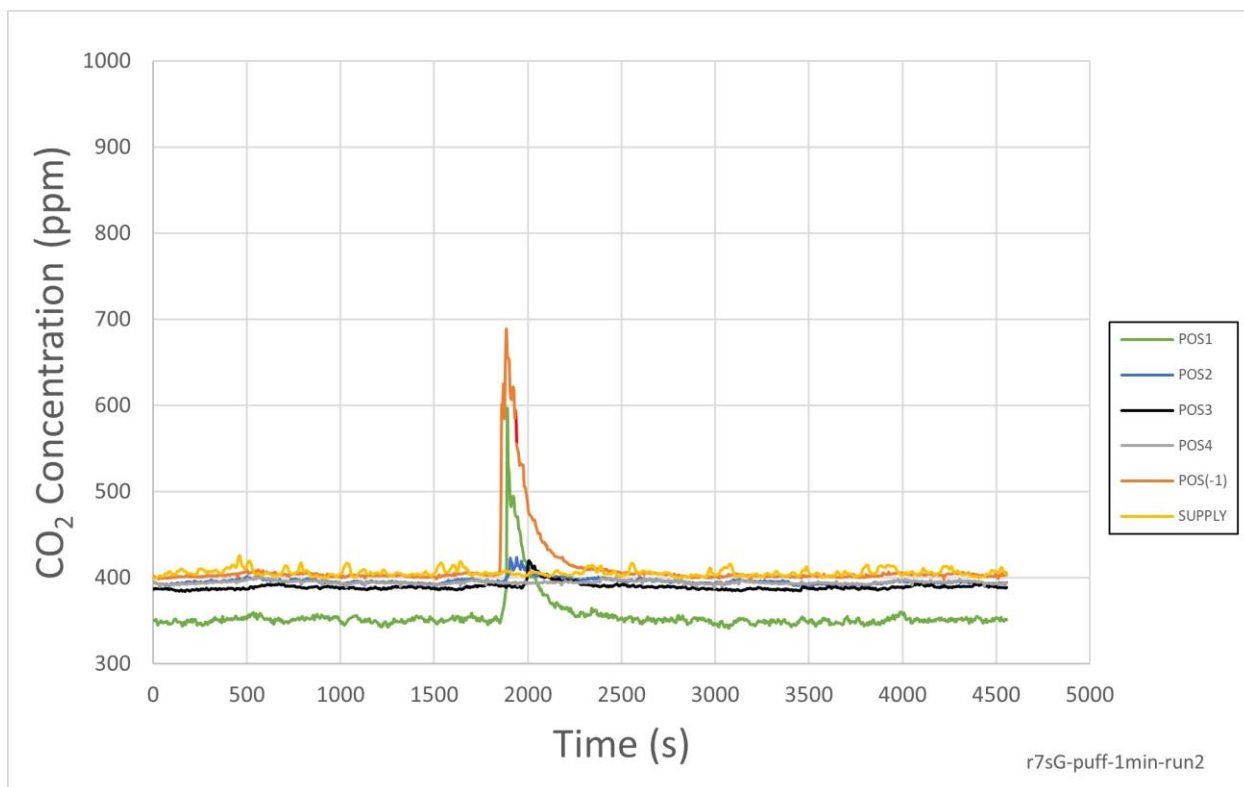
Appendix D D.20: Row 7 Seat G – 3-Minutes Puff – Run 20



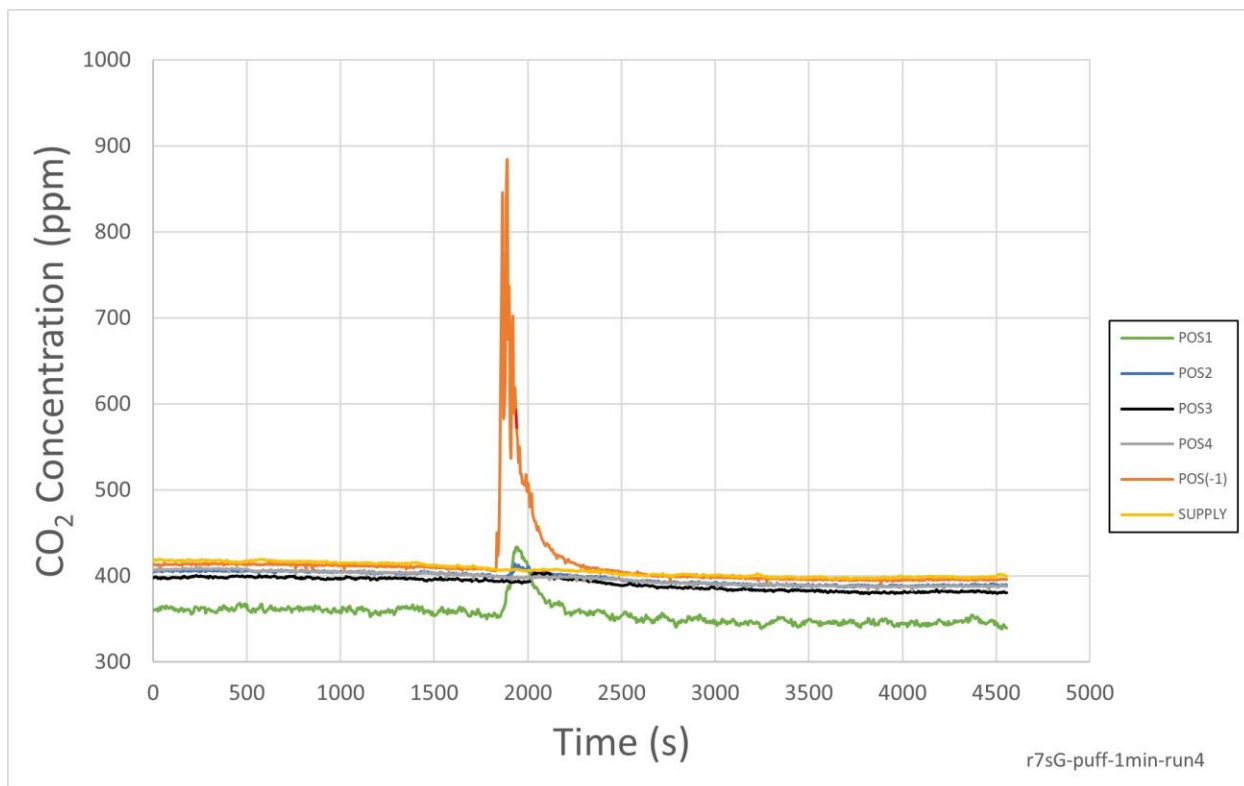
Appendix D D.21: Row 7 Seat G – 3-Minutes Puff – Run 21



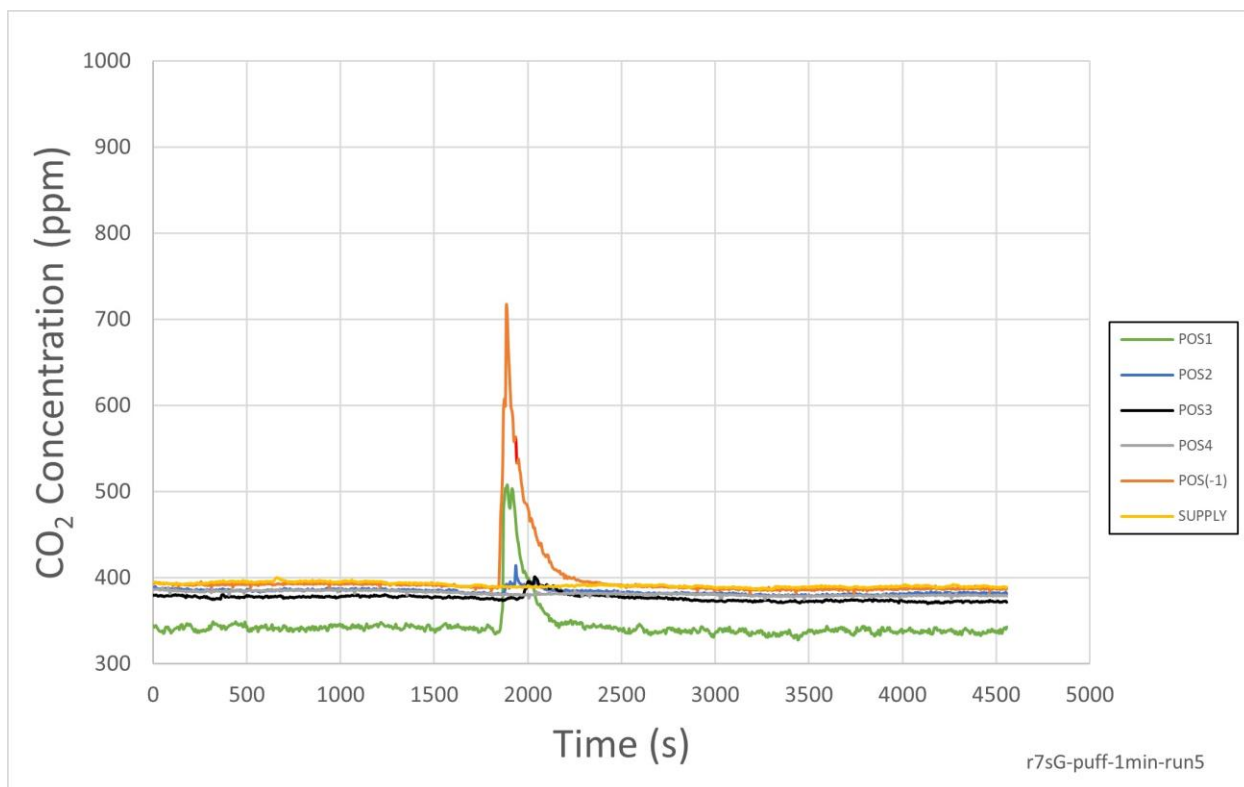
Appendix D D.22: Row 7 Seat G – 3-Minutes Puff – Run 22



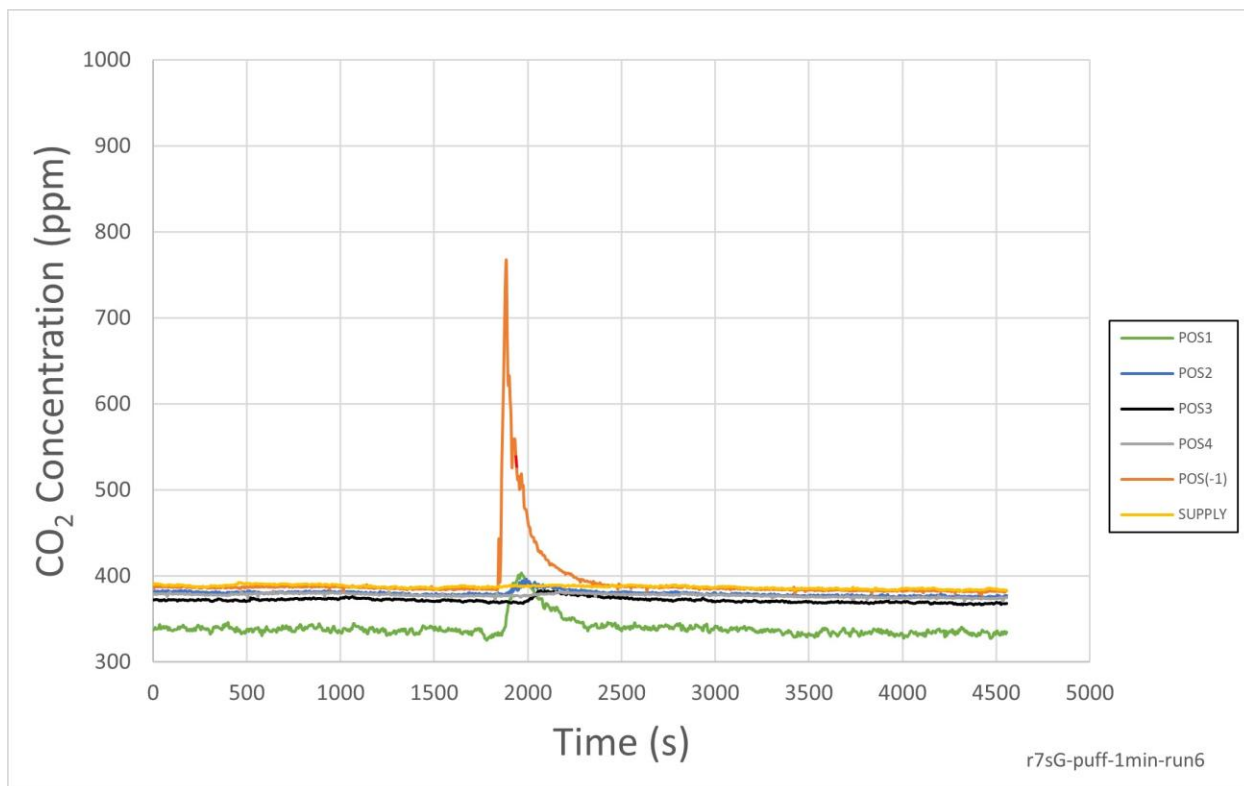
Appendix D D.23: Row 7 Seat G – 1-Minute Puff – Run 1



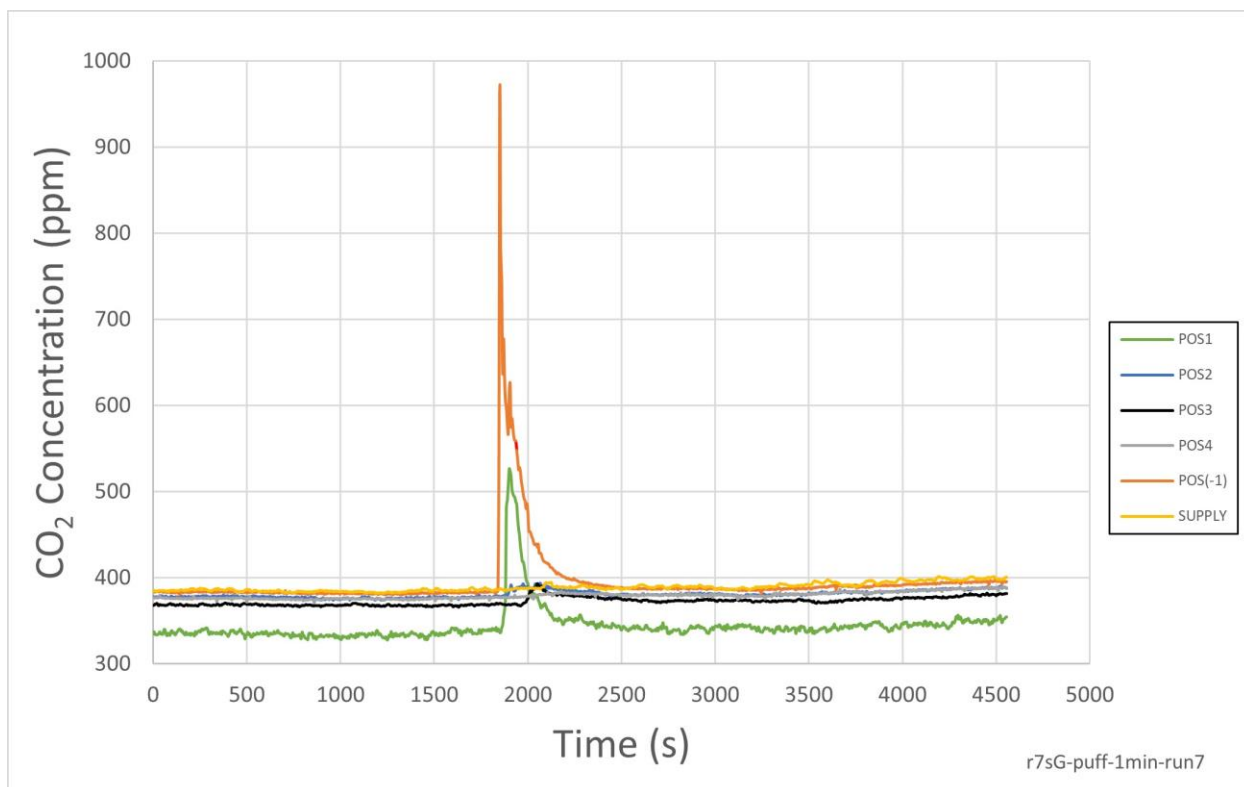
Appendix D D.24: Row 7 Seat G – 1-Minute Puff – Run 2



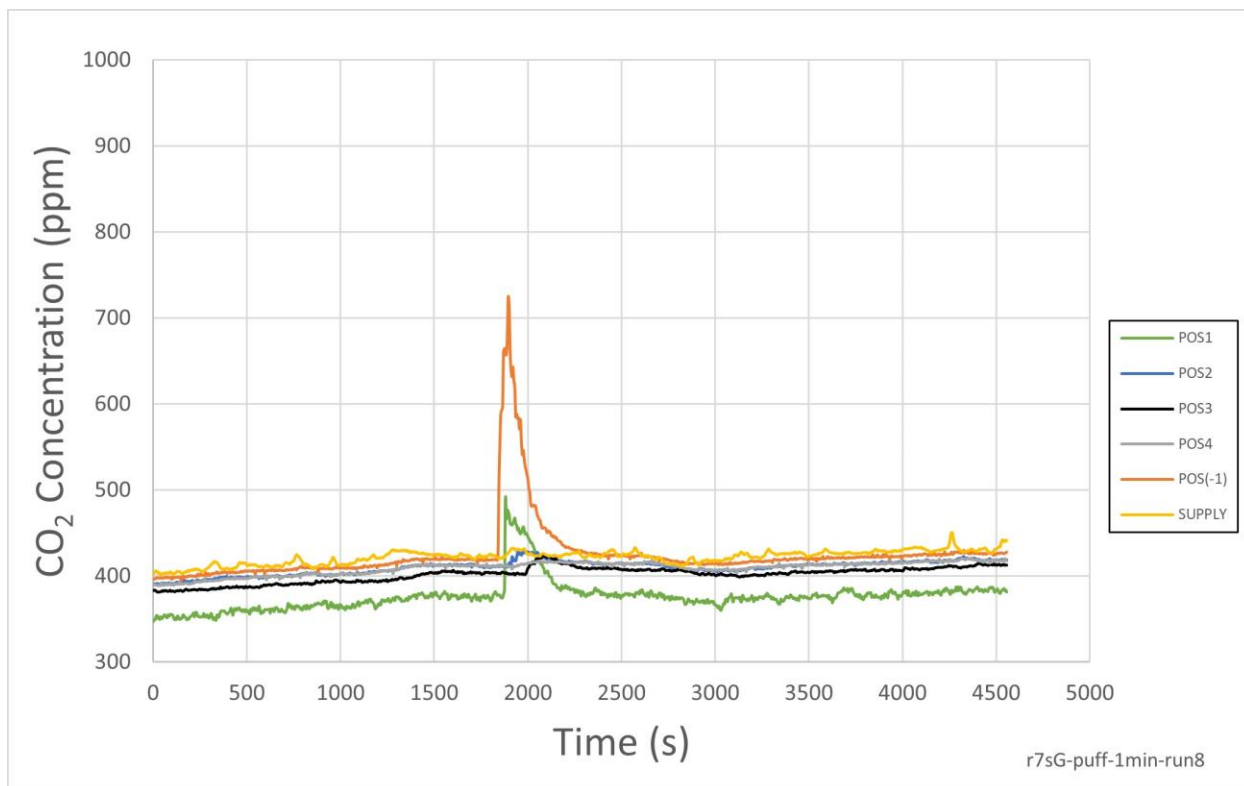
Appendix D D.25: Row 7 Seat G – 1-Minute Puff – Run 3



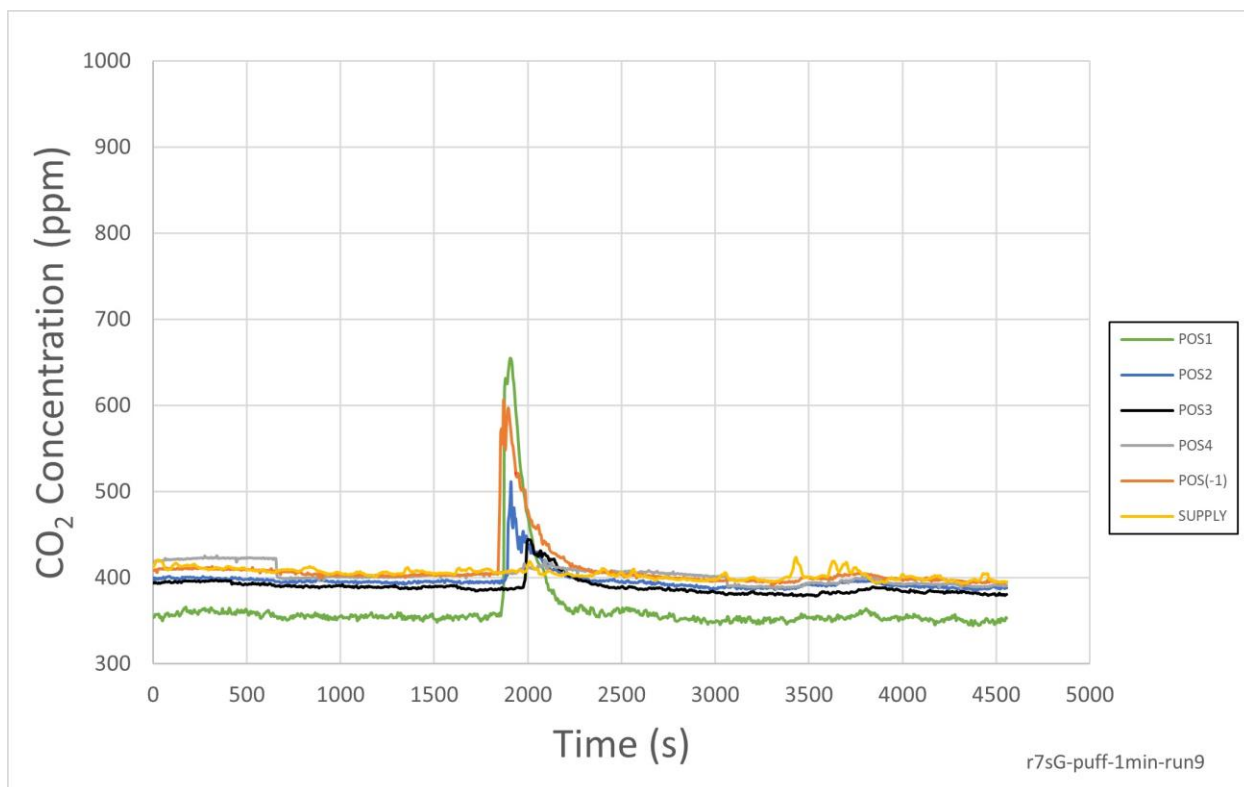
Appendix D D.26: Row 7 Seat G – 1-Minute Puff – Run 4



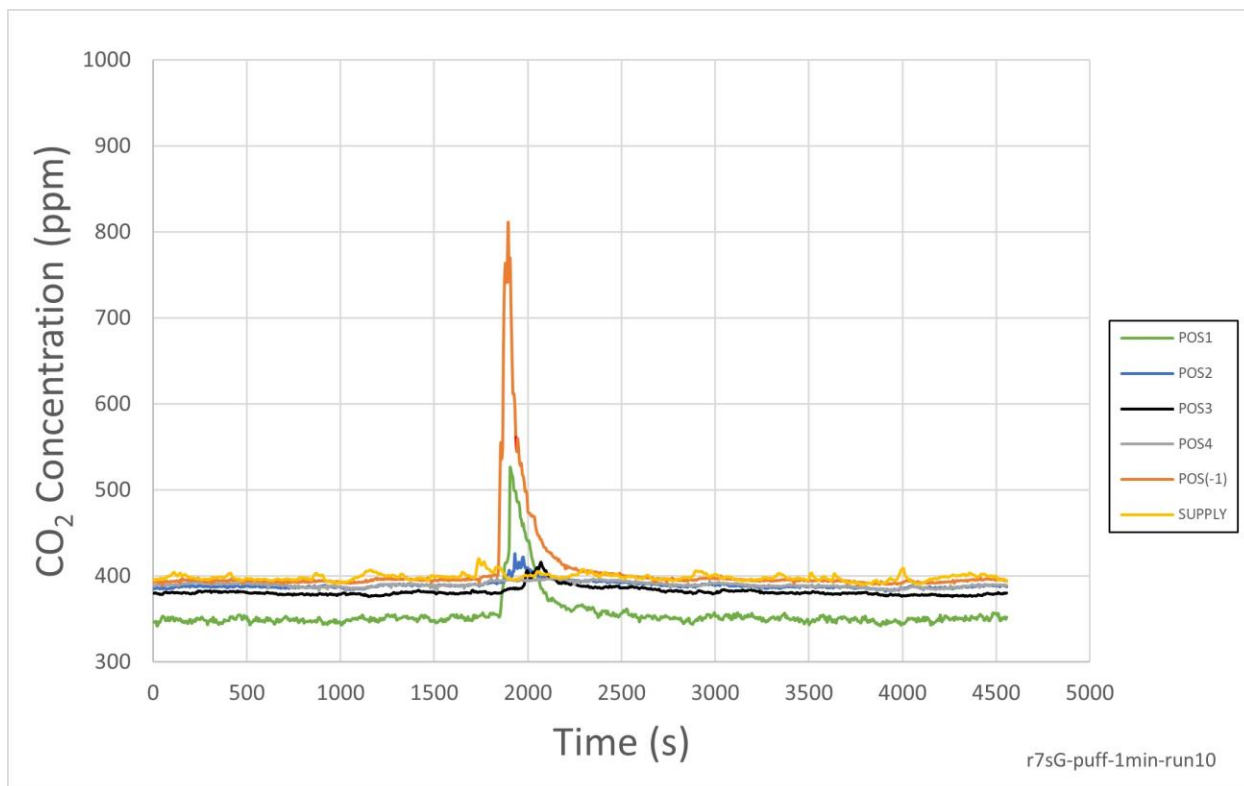
Appendix D D.27: Row 7 Seat G – 1-Minute Puff – Run 5



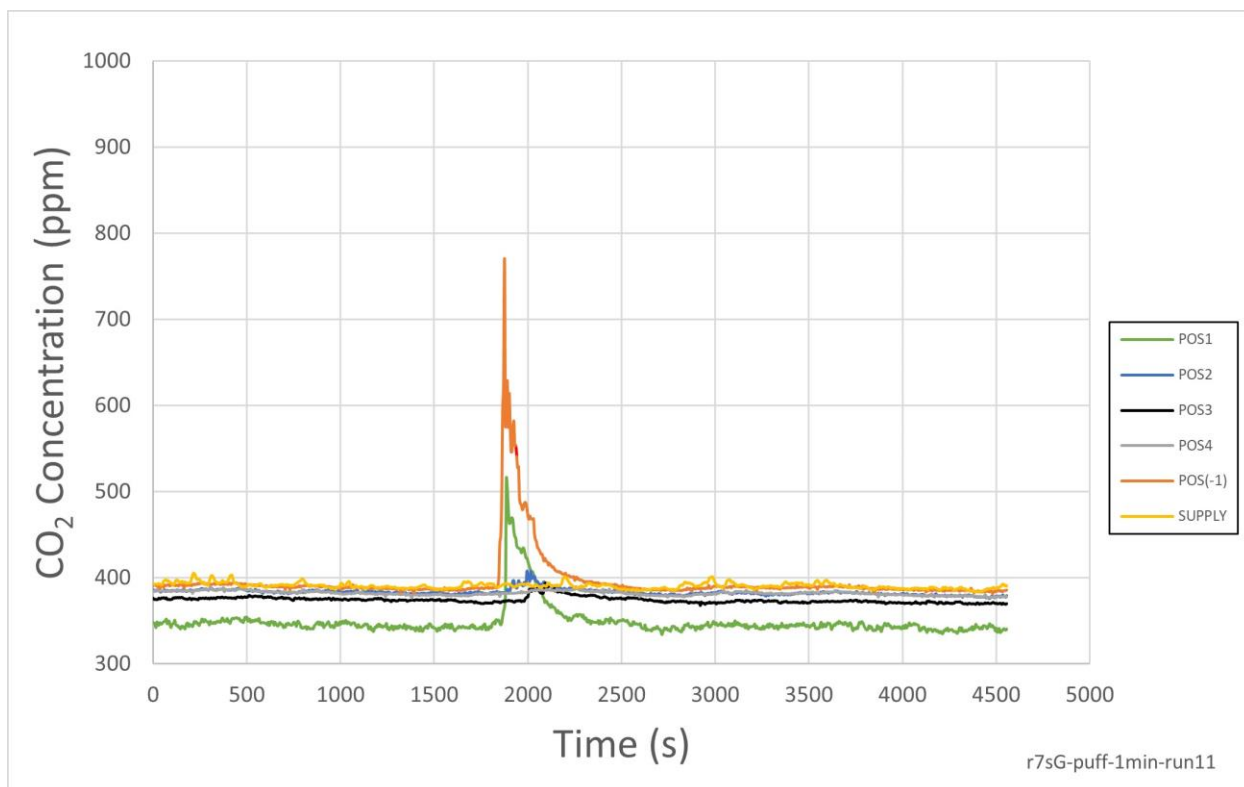
Appendix D D.28: Row 7 Seat G – 1-Minute Puff – Run 6



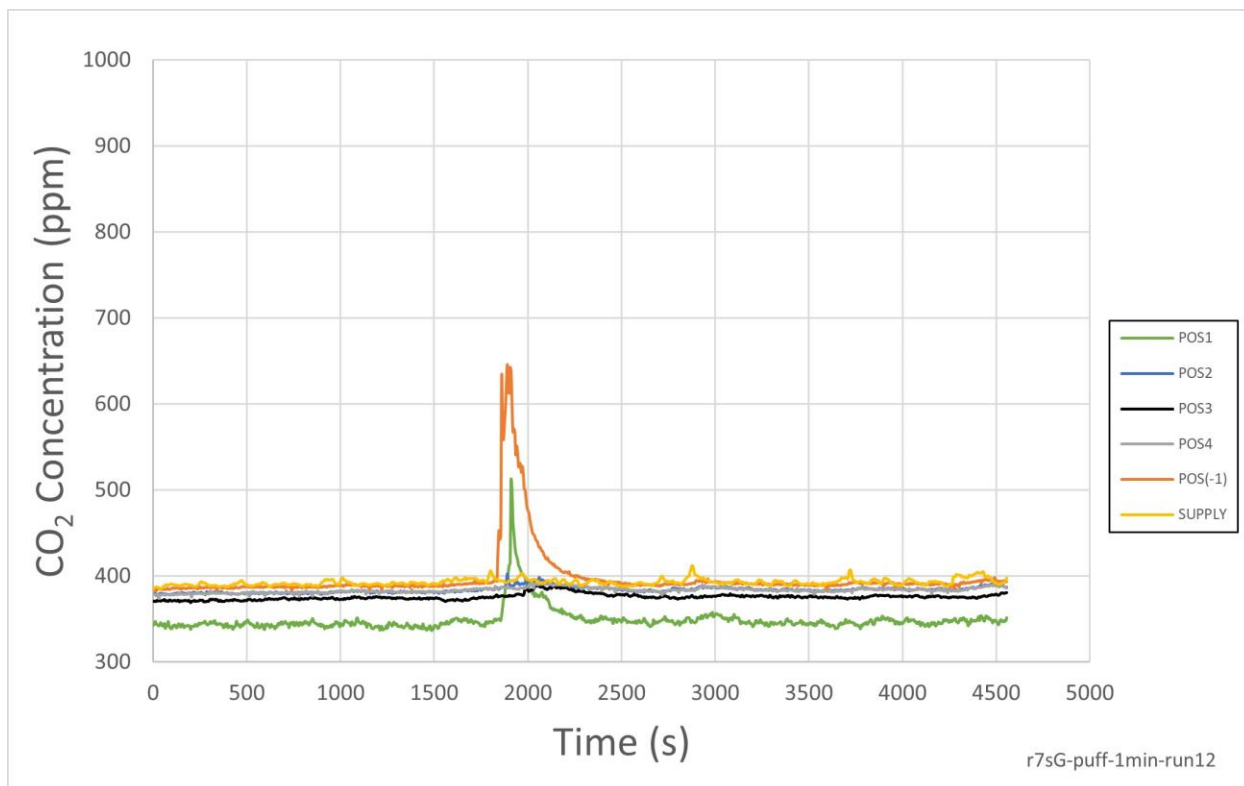
Appendix D D.29: Row 7 Seat G – 1-Minute Puff – Run 7



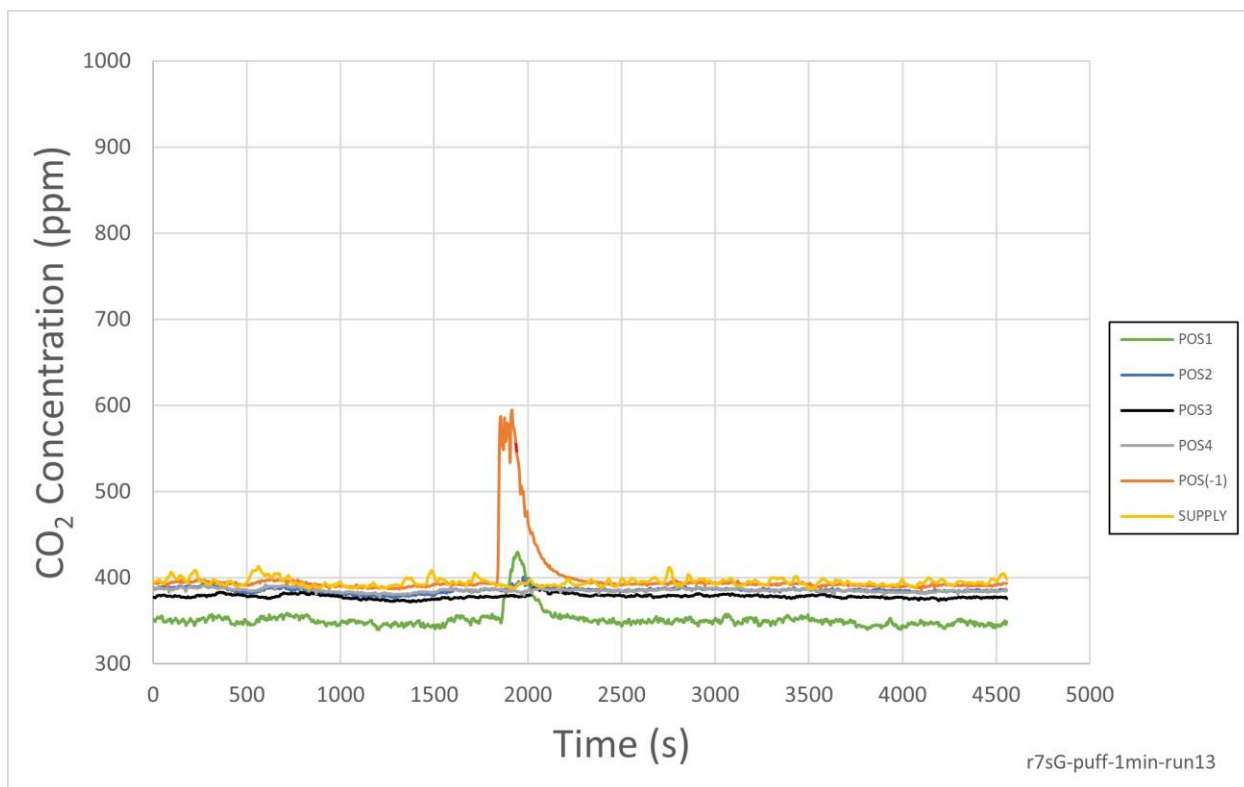
Appendix D D.30: Row 7 Seat G – 1-Minute Puff – Run 8



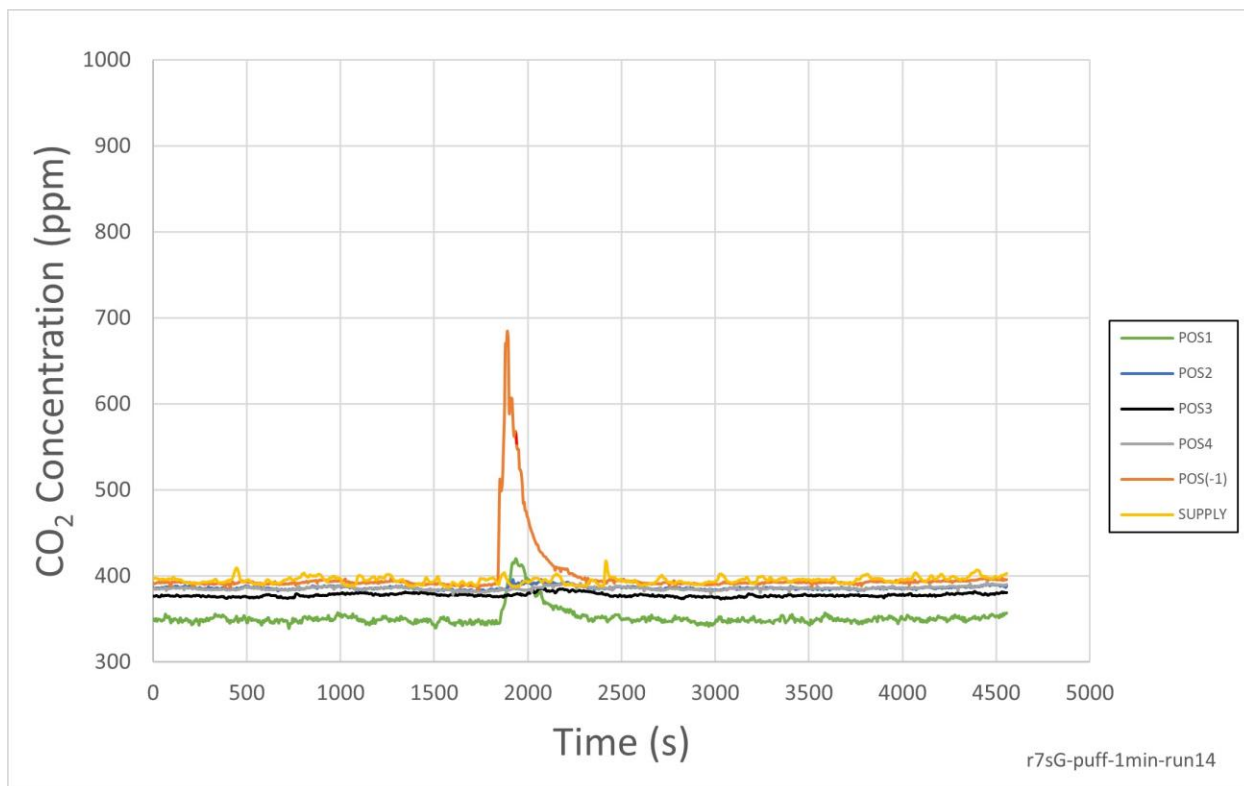
Appendix D D.31: Row 7 Seat G – 1-Minute Puff – Run 9



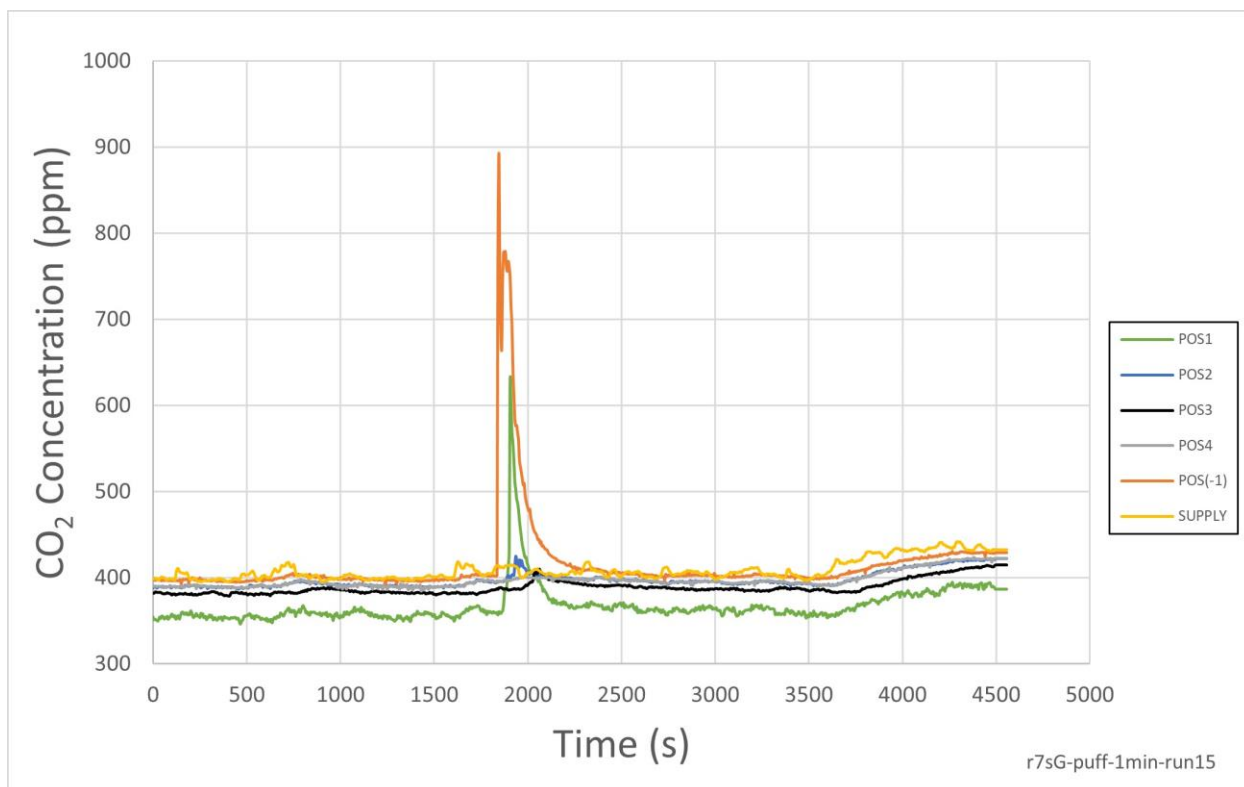
Appendix D D.32: Row 7 Seat G – 1-Minute Puff – Run 10



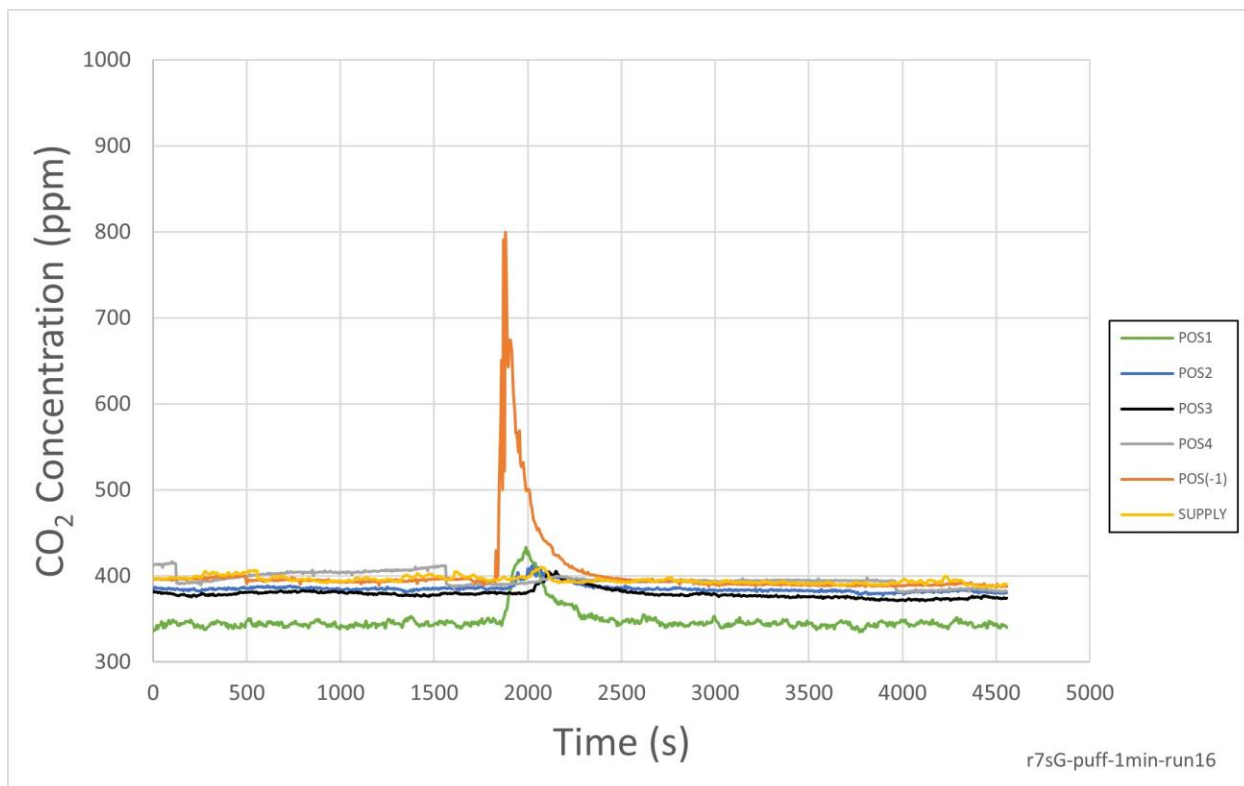
Appendix D D.33: Row 7 Seat G – 1-Minute Puff – Run 11



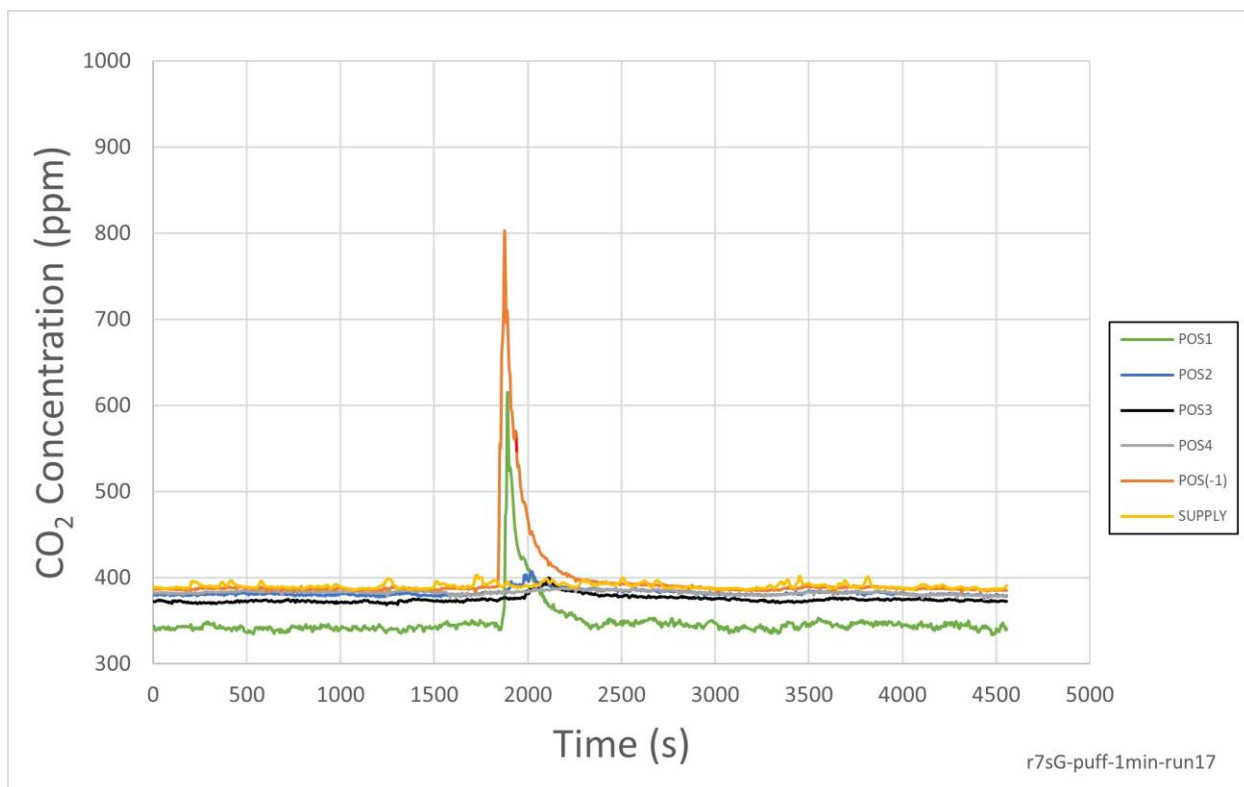
Appendix D D.34: Row 7 Seat G – 1-Minute Puff – Run 12



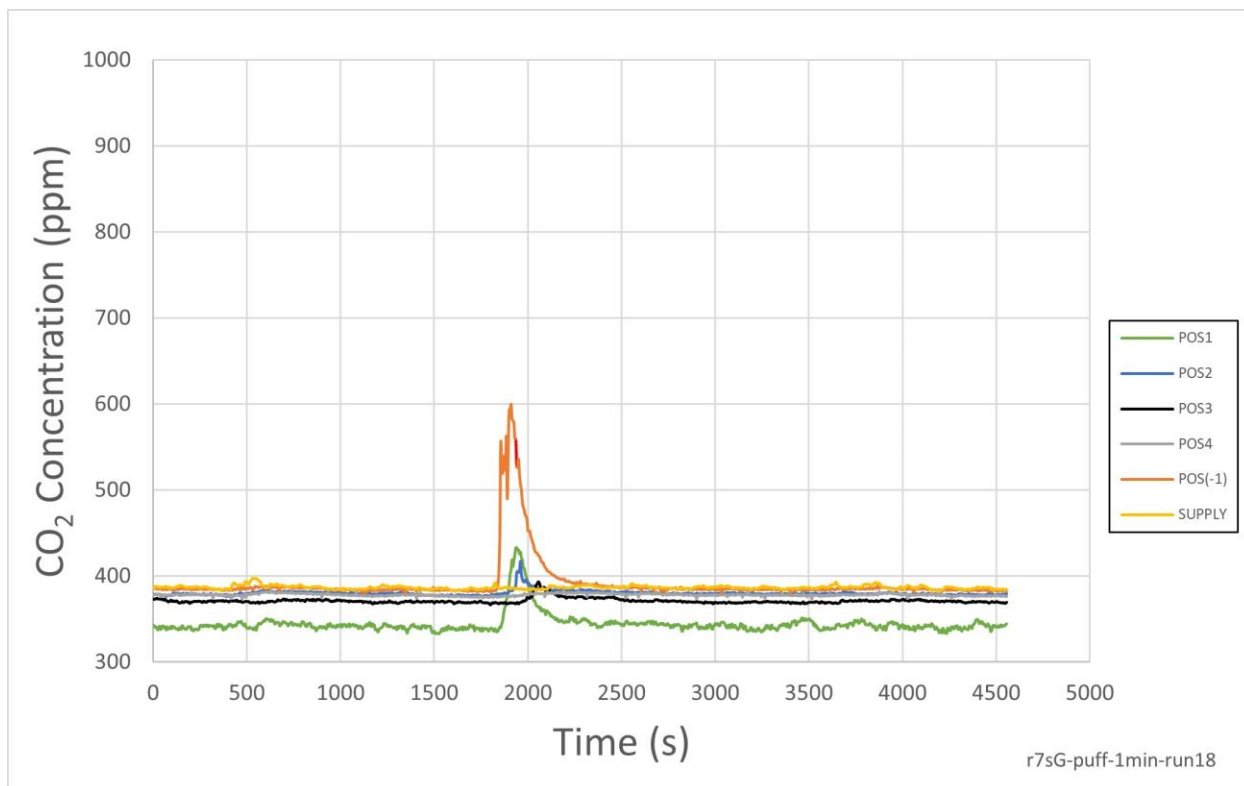
Appendix D D.35: Row 7 Seat G – 1-Minute Puff – Run 13



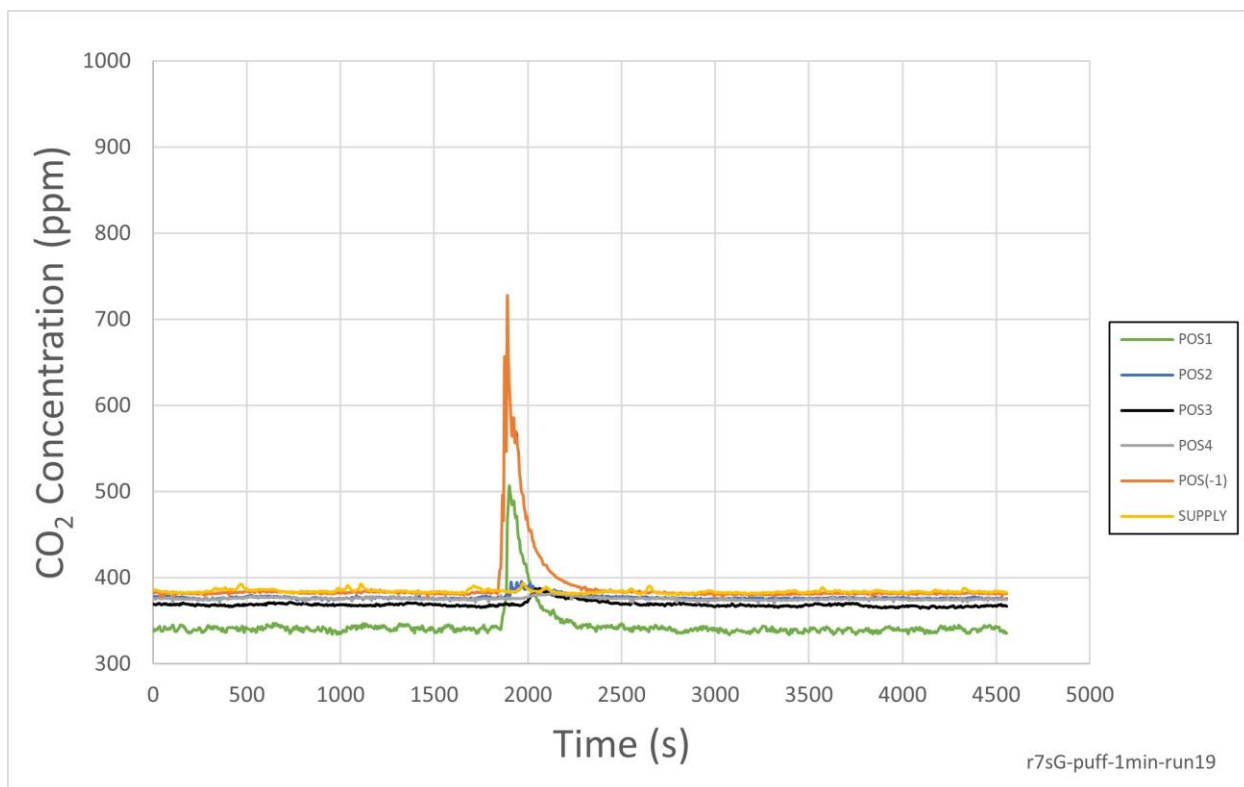
Appendix D D.36: Row 7 Seat G – 1-Minute Puff – Run 14



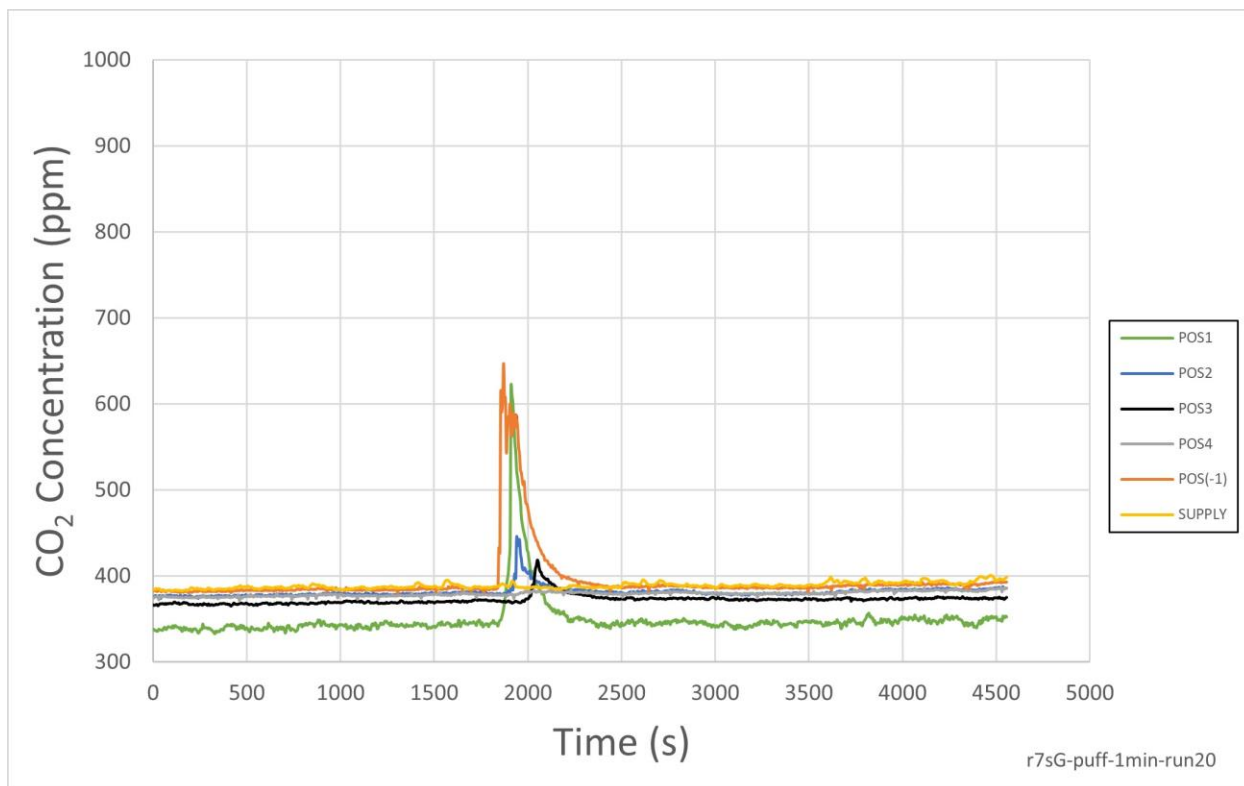
Appendix D D.37: Row 7 Seat G – 1-Minute Puff – Run 15



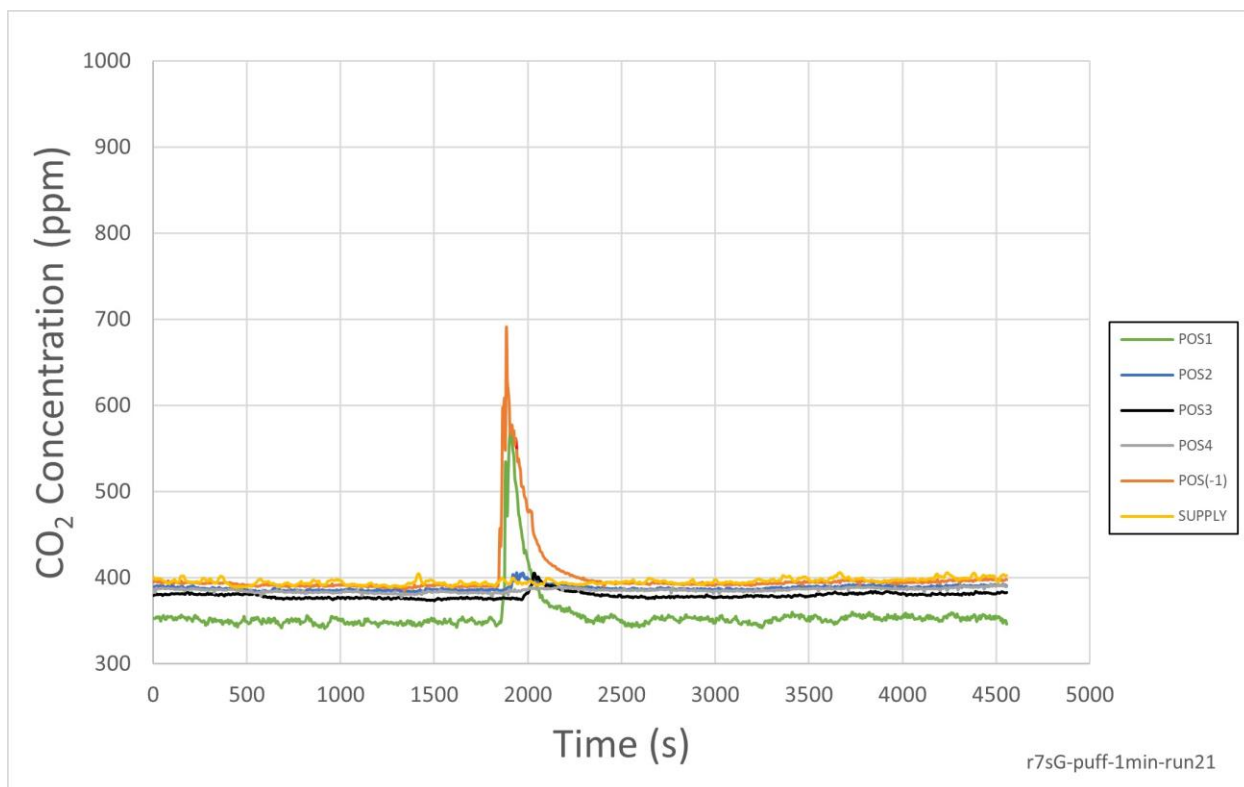
Appendix D D.38: Row 7 Seat G – 1-Minute Puff – Run 16



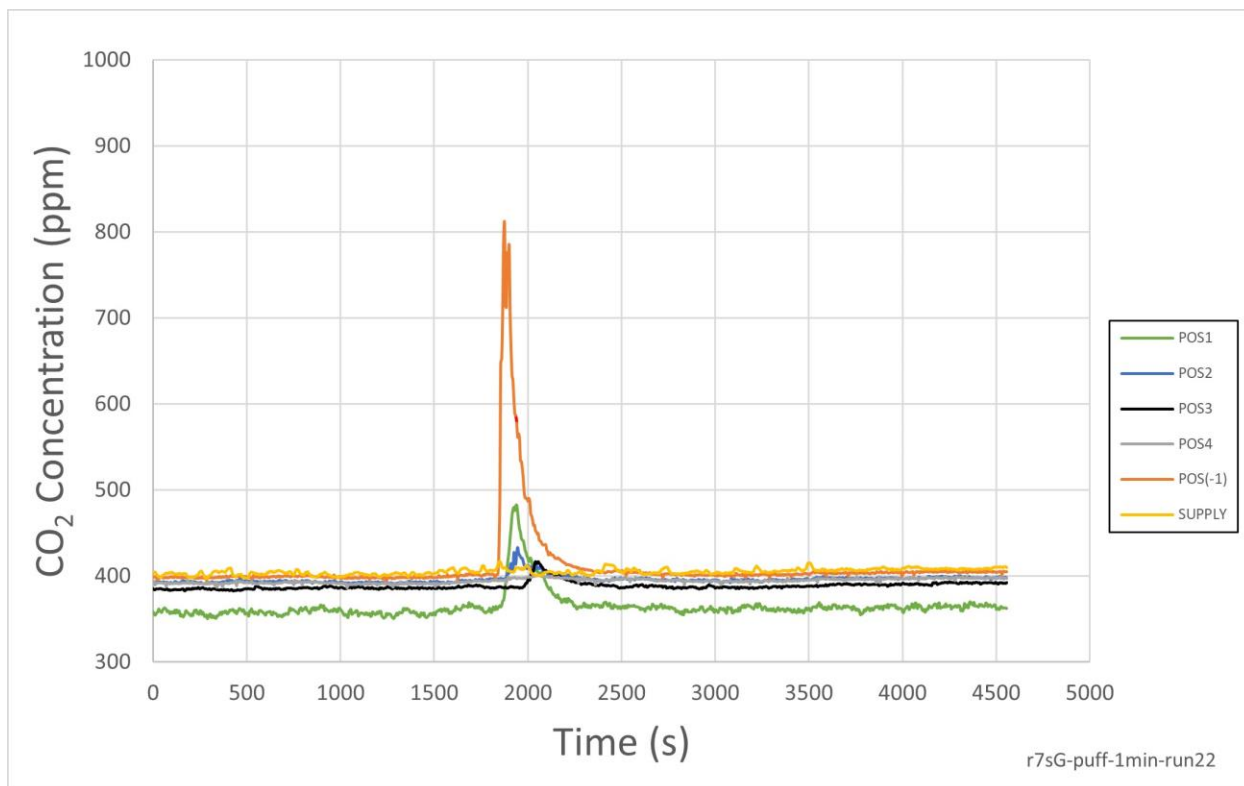
Appendix D D.39: Row 7 Seat G – 1-Minute Puff – Run 17



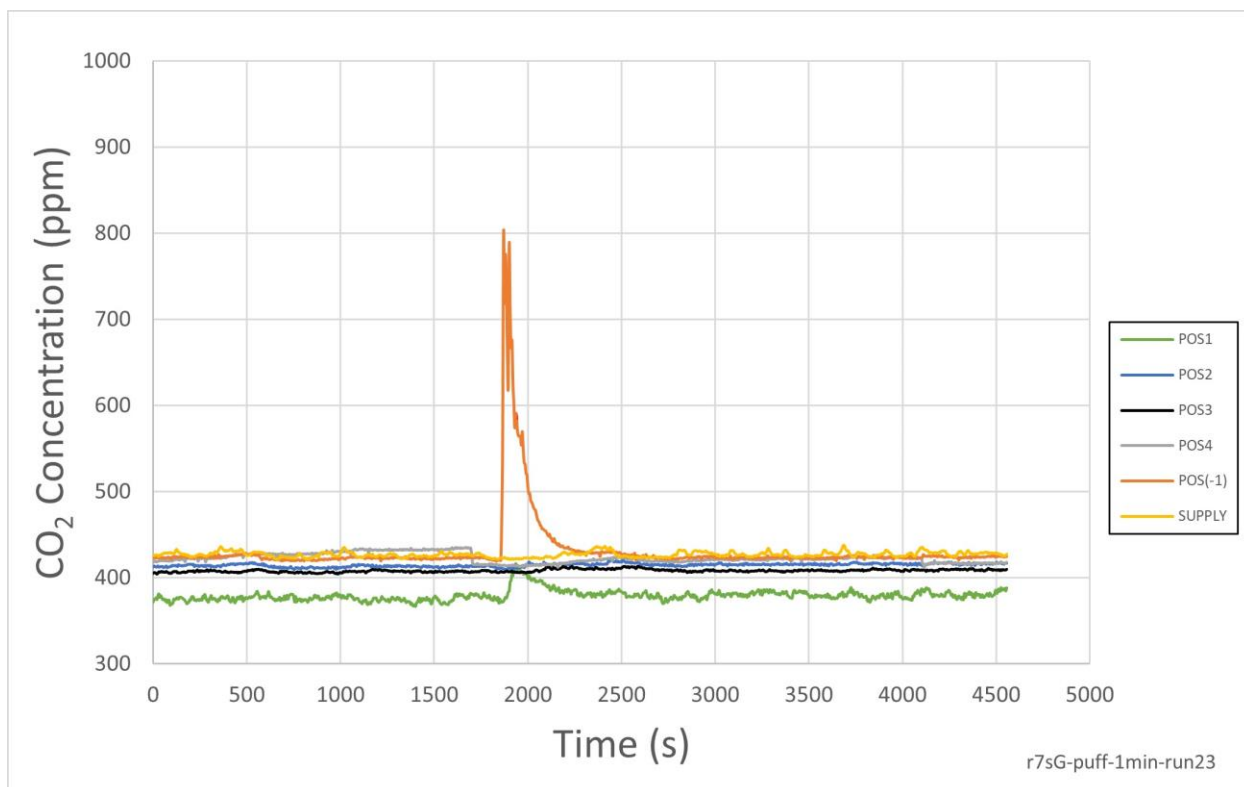
Appendix D D.40: Row 7 Seat G – 1-Minute Puff – Run 18



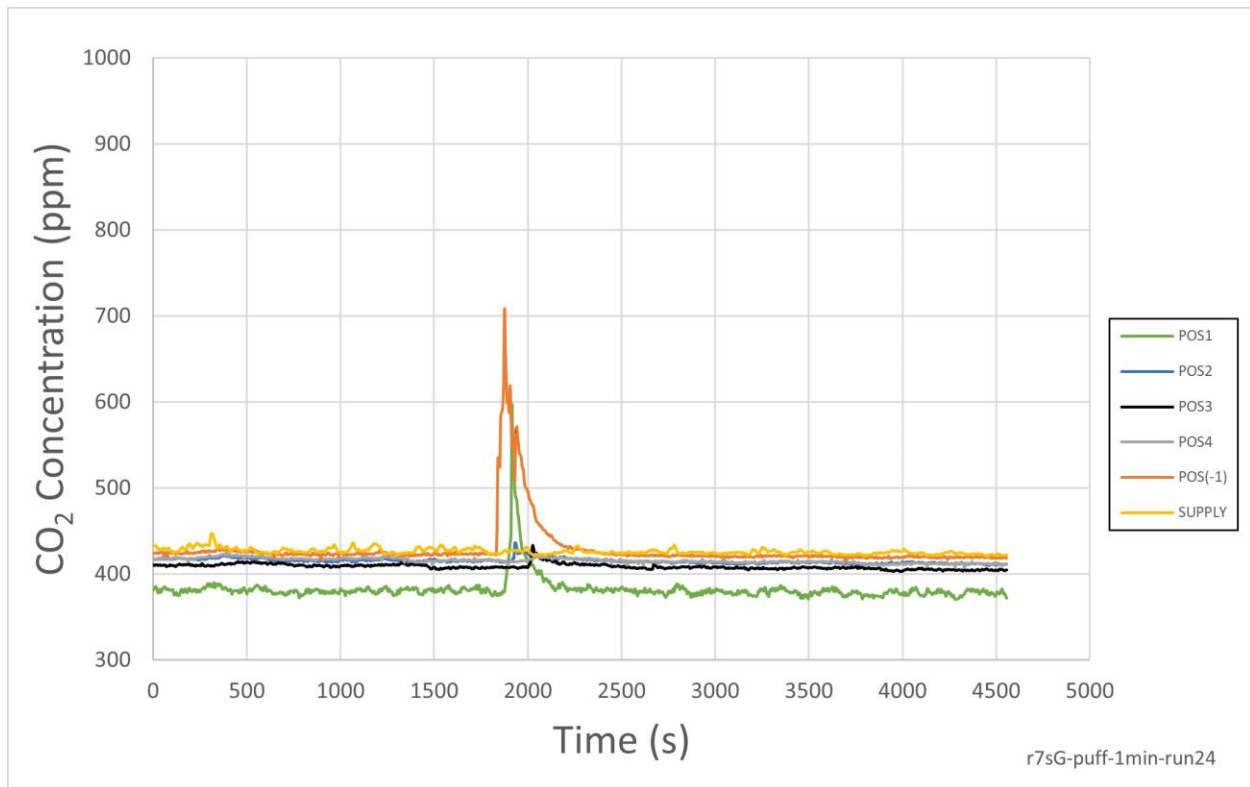
Appendix D D.41: Row 7 Seat G – 1-Minute Puff – Run 19



Appendix D D.42: Row 7 Seat G – 1-Minute Puff – Run 20



Appendix D D.43: Row 7 Seat G – 1-Minute Puff – Run 21



Appendix D D.44: Row 7 Seat G – 1-Minute Puff – Run 22