NATIONAL TRANSPORTATION SAFETY BOARD

Office of Research and Engineering
Materials Laboratory Division
Washington, D.C. 20594

March 22, 2019

MATERIALS LABORATORY STUDY REPORT Report No. 18-039S

A. ACCIDENT INFORMATION

Place	:	Silver Spring, Maryland
Date	:	August 10, 2016
Vehicle	:	Washington Gas service pipe and gas regulators
NTSB No.	:	DCA16FP003
Investigator	:	Rachael Gunaratnam, O-RPH

B. COMPONENTS EXAMINED

1. Meter room at 8701 Arliss Street, Silver Spring, MD

C. DETAILS OF THE EXAMINATION

The study report supports the investigation of a building explosion and fire at 8701 Arliss Street, Silver Spring, MD (Flower Branch Apartment Building). The purpose of this study is to computationally estimate the time necessary for a venting natural gas regulator to create and atmosphere in the 8701 Arliss St. meter room[1] with natural gas at a concentration sufficient to support an explosive event.

The following general assumptions have been made to support the calculations and models:

Location of the Explosion in the 8701Arliss Street Building

1. The Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) report states that the explosion occurred in the meter room (Figures 1 and 2)[2].

Timeframe for the Natural Gas Accumulation in the Meter Room and the Explosion

1. Based on witness reports of audible and olfactory indices, there was no evidence of a natural gas leak when the room was last occupied at 8:42 p.m EST[3]. The explosion occurred at 11:51 p.m. EST, suggesting that there was a 3.15 h duration between the last time the room was occupied and the explosion[4].

[1] Also referred to as the utility room in some NTSB reports.
[2] NTSB Docket DCA16FP003 - ATF Report.
[3] NTSB Docket DCA16FP003 - Vector Security Report on Doors Access.
[4] NTSB Docket DCA16FP003 - Operations Report.

Meter Room Dimensions, Volume, and Construction

1. Based on the Washington Gas laser scanning measurements and the Kay Management drawing dimensions, Figure 2 represents the best estimate for size and shape of the meter room. Using post-accident photographs, the room height was estimated to be 11 CMU (concrete masonry units) high (about 7.3 ft)[5].
2. Kay Management provided a full inventory of the items stored in the meter room. In aggregate, the room had an estimated 128 ft^3 of items that would not readily fill with natural gas.[6] Additionally, the water heater occupied approximately 20 ft^3 of room volume.
3. The walls in the meter room were CMU and other bricks. The ceiling and floor were concrete.
4. The room volume was calculated per the following equation

$$V_{empty} = ((28.9ft \times 17.5ft) + (12.0ft \times 4.1ft)) \times 7.3ft = 4051.0ft^3$$

$$V_{effective} = V_{empty} - V_{hot\ water\ heater} - V_{stored\ items}$$

$$V_{effective} = 4051ft^3 - 20ft^3 - 128ft^3 = 3903ft^3$$

Where V_{empty} is the approximate volume of the empty meter room, $V_{hot\ water\ heater}$ is the volume of the water heater, $V_{stored\ items}$ is the volume of the stored items, and $V_{effective}$ is the volume of the meter room that could be effectively filled with a natural gas-air mixture.

Source of the Natural Gas Leak to the Meter Room

1. The jurisdictional natural gas supply to the meter room was through a 2 inch nominal pipe size (NPS) steel pipe with a pressure ranging between 20 psig and 22 psig at the time of the accident. The pipe entered the west CMU wall in the north-west corner of the meter room about 60 inches from the floor and fed a vertical manifold with two mercury-type natural gas pressure regulators. The pressure regulators reduced the operating pressure to the meters to 6 inches water column. The pressure regulators vented to a common vertical pipe that exited the west CMU wall in the north-west corner about 74 inches from the floor[7].
2. A 3/4 inch national pipe thread (NPT) union for the lower gas pressure regulator vent line was found disconnected after the accident[8].
3. Based on accident scene photographs, the lower pressure regulator union is about 24 inches from the meter room floor.

---

[5] CMU is a concrete masonry unit, also know as a concrete block or cinder block, 16 inch × 8 inch × 8 inch.
[6] NTSB Docket DCA16FP003 Operations Report.
[7] NTSB Docket DCA16FP003 Operations Report.
[8] NTSB Docket DCA16FP003 Operations Report. NTSB Docket DCA16FP003 - ATF Report.

Nature of the Natural Gas Supply to the Meter Room

1. Washington Gas indicated that the specific natural gas composition at the time of the accident would have a lower explosive limit (LEL) of 4.8% by volume[9].

Evaluation of Exemplar Natural Gas Pressure Regulators

1. Five mercury gas pressure regulators of the same make and model and of similar in age to the accident regulators in the 8710 Arliss Road meter room were removed from other meter rooms at the Flower Branch Apartment Building complex for exemplar testing of failure and vent leak characteristics as listed below[10].

Regulator failure condition	Vent flow rate
Perforated diaphragm with both regulator vents active with no houseline demand (diaphragm tear)	$R_{perf-dia} = 2190\ \text{SCFH} = 36.5\ \text{SCFM}$
Perforated diaphragm with both regulator vents active with low-load houseline demand (diaphragm tear)	$R_{perf-dia-hl} = 1920\ \text{SCFH} = 32.0\ \text{SCFM}$
Total loss of mercury in the regulators	$R_{Hg-loss} = 331\ \text{SCFH} = 5.5\ \text{SCFM}$
Failed open regulator, an 0.034 inch diameter wire between the valve and the seat orifice (valve seat obstruction)	$R_{failed-open} = 165\ \text{SCFH} = 2.8\ \text{SCFM}$

Sources of Natural Gas Ignition in the Meter Room

1. For a natural gas explosion to occur, a gas mixture in the range of 3.9 % (lower explosive limit—LEL) to 15 % (upper explosive limit—UEL) by volume natural gas in air must be near an ignition source (electric spark, hot surface, or flame)[11].
2. Multiple sources of ignition are present in the meter room. The primary ignition sources considered in this report are[12]:
   a. Water heater's pilot with intermittent electronic ignition (when active).
   b. Water heater main burner (when the water heater is cycling for recovery).
   c. Electrical sparks or hot surfaces in one or more of the fifteen electric meters installed in a bank in the north east corner of the meter room.
   d. Electrical sparks or hot surfaces within the electrical panel and fusible disconnect located in the north east corner of the meter room.
   e. Lighting or lighting circuitry within the meter room.

[9] NTSB Docket DCA16FP003 - Gas Composition on August 10, 2016 to Flower Branch Complex
[10] Regulator vent flow rates were determined from field tests at the Washington Gas facility in Springfield, VA in October 2016 and May 2017. The results are in NTSB Docket DCA16FP003 - Exemplar Mercury Regulator Test Report TR-2016-1.0 and Mercury Regulator Battery Test Report TR2017-1.0.
[11] NFPA 921, *Guide for Fire and Explosion Investigations*, National Fire Protection Association, Quincy, MA, 2017.
[12] NTSB Docket DCA16FP003 - ATF Report.

Meter Room Ventilation and Fresh Make-Up Air.

1. Passive venting is required in the meter room to allow make-up air to the water heater to support combustion (with excess air) and to enable positive ventilation of its combustion gas byproducts.
2. A Kay Management representative indicated that one of the meter room windows (in a well just below grade level) was modified to allow continuous passive venting.
3. The water heater located in the meter room was a State Industries model SBD81-199-NE with the following specifications: 81 gallon water capacity, 200,000 btu/h burners, 34.00 inch diameter by 74.50 inch tall[13]. The water heater occupied a cylindrical volume of 20 ft^3. The water heater was positioned in the north-east corner of the meter room. The manufactured-specified water heater exhaust vent diameter was 6 inch.
4. It is assumed that the water heater is vented in compliance with the local code and a version of the National Fuel Gas Code (ANSI-Z223.1) Category I Venting Tables (or something similar at the time of construction), using a dedicated 6 inch diameter chimney exhaust stack[14]. The make-up air vent to outside is assumed to be no less than 66 in^2. Passive venting is assumed to occur through natural convection (no powered or forced convection).
5. Based on the NB-132 code[15], boilers operating at 500,000 btu/h need 125 CFM of makeup air and a vent area of 144 in^2. In proportional scaling to 200,000 btu/h, there needs to be about 50 CFM of makeup air and 58 in^2 vent opening. Some manufacturers specify make-up air volumetric flow rates on the order of 0.24 to 0.47 SCFM/kBtu/h[16].
6. According to the ATF report, at the time of the explosion, the outside temperature was 80 °F and the air was still[17]. When the water heater was operating, it is assumed that there was positive ventilation in the meter room. When the water heater was not operating it was assumed that some amount of natural gas could vent outside the room due to minor pressure difference between the interior and exterior of the meter room and minor ventilation stack venturi effects.

[13] NTSB Docket DCA16FP003 - Hot Water Heater Unit Operating and Service Manual.
[14] AGA - ANSI Z223.1 National Fuel Gas Code Handbook, American Gas Association, Washington, DC.
[15] *Recommended Administrative Boiler and Pressure Vessel Safety Rules and Regulations*, The National Board of Boiler & Pressure Vessel Inspectors, Columbus, OH, October 25, 2004.
[16] Y. Utiskul, et. al., *Combustion Air Requirements for Power Burner Appliances*, The Fire Protection Research Foundation, Quincy, MA January 2012.
[17] NTSB Docket DCA16FP003 - ATF Report

D. CLOSED-FORM CALCULATION

Based on the volumetric flow rate of natural gas from a failed gas pressure regulator, the time to fill the meter room with a combustible mixture of natural gas in air at the lower flammability limit (LEL) was calculated. The general assumptions in Section C apply.

The following specific assumptions are made for the closed-form calculation.

1. The leaked natural gas mixes instantaneously and homogeneously in the meter room by natural convection.
2. All processes transpired at standard temperature and pressure (STP).
3. No natural gas venting or fresh air exchanges are assumed to occur.
4. No low-load, houseline demand was assumed.

The time required to reach a critical gas concentration in the room (assuming instantaneous and homogeneous mixing) is represented by the following equation.

$$t_c = \frac{V \times C_a}{R_b}$$

Where

t_c is the time to reach critical natural gas concentration (in minutes).

V is the meter room volume (in ft^3) based on the architectural drawing for the meter room shown in Figure 1. The volume of the meter room is estimated according to the equation below.

$$V = V_{effective} = 3903\ ft^3$$

C_a is the critical gas concentration at a specific case (where a could be LEL, or UEL) as indicated in the table below.

		Critical gas concentration	
Explosive limit, a	Symbol, a	C_a (%)	C_a
Lower explosive limit, LEL	C_{LEL}	4.8	0.048

R_b is the experimentally-determined regulator vent flow rate (in SCFM), and b is one of four scenarios as shown in the table below[18].

		Vent flow rate	
Regulator failure condition, b	Symbol, b	R_b (SCFH)	R_b (SCFM)
Perforated diaphragm with both regulator vents active with no houseline demand (diaphragm tear), *perf-dia*	$R_{perf-dia}$	2190	36.5
Perforated diaphragm with both regulator vents active with low-load houseline demand (diaphragm tear), *perf-dia-hl*	$R_{perf-dia-hl}$	1920	32.0
Total loss of mercury in the regulators, *Hg-loss*	$R_{Hg-loss}$	331	5.5
Failed open regulator, an 0.034 inch diameter wire between the valve and the seat orifice (valve seat obstruction), *failed-open*	$R_{failed\ open}$	165	2.8

A summary of the times required to reach the LEL gas concentration in the room, t_c, based on the regulator vent volumetric leak flow rates above are summarized in the table below for four different pressure regulator failure scenarios.

Flammability limit, a	Case*	Gas regulator status, b	t_c (min)	V (ft^3)	C_a	C_a (%)	R_b (SCFM)
LEL	A	*perf-dia*	5	3903	0.048	4.8	36.5
LEL	B	*perf-dia-hl*	6	3903	0.048	4.8	32.0
LEL	C	*Hg-loss*	34	3903	0.048	4.8	5.5
LEL	D	*failed-open*	67	3903	0.048	4.8	2.8

*A. Perforated diaphragm with both regulator vents active, perf-dia.
B. Perforated diaphragm with both regulator vents active with low-load houseline pressure, perf-dia-hl.
C. Total loss of mercury in the regulators, Hg-loss.
D. Failed open regulator, an 0.034 inch diameter wire between the valve and the seat orifice, failed-open.

[18] Regulator vent flow rates were determined from field tests at the Washington Gas facility in Springfield, VA in October 2016 and May 2017. The results are in NTSB Docket DCA16FP003 - Exemplar Mercury Regulator Test Report TR-2016-1.0 and Mercury Regulator Battery Test Report TR2017-1.0.

E. COMPUTATIONAL FLUID DYNAMICS (CFD) MODEL OF THE METER ROOM GAS CONCENTRATION

The temporal natural gas concentration as a function of spatial position in the meter room was determined using the assumptions discussed in Section C. The computations were made using FDS[19] and PyroSim[20].

The meter-room spatial-arrangement of the computational model is illustrated in Figure 3 and 4. The computational domain of the model contains a total volume of 110.5 m^3. This computational domain is divided into a rectilinear grid with a nominal cell size of 0.1m x 0.1m x 0.1m. A vent with an area of 0.06 m^2 representing the basement window is included near the leakage gas source. A vent with an area of 0.02 m^2 representing the leakage around the entry door is included at the location of the entry door. A rectangular obstruction representing the water heater was placed in the area where the water heater was believed to have been installed. At the base of this water heater, exhaust vents were placed to simulate the combustion air intake for the water heater. In the instance where the water heater was modeled as being active, these vents would draw in a total of 50 CFM of air. Other obstructions in the computational domain such as gas and electric meters are inert objects.

The flow rate of the leaking natural gas used in the model was chosen from the results of the field tests at the Washington Gas facility in Springfield, VA[21]. The lowest leakage rate of 165 SCFH determined during the “valve seat obstruction” test was chosen. The field tests also showed that the leakage flow rate would decrease when there was a low load demand for gas. For the purposes of this model it is assumed that the leakage flow rate from the regulator decreases to zero when the water heater is active. The source location of the gas leakage in the computational domain represents the open union found at the lower regulator.

Two cases with the same gas leakage flow rate were modeled.

1. Case 1: The water heater is dormant for the duration of the model and the natural gas flow rate from the open union is a constant 165 SCFH.
2. Case 2: The water heater is off for 40 minutes and on for 20 minutes repeatedly for the duration of the model and the natural gas flow rate from the open union is 165 SCFH when the water heater is not active.

Both cases showed a buoyant plume of natural gas ascending to the ceiling and spreading outward until reaching the walls. Upon reaching the walls the gas began to build a concentration gradient from the ceiling towards the floor.

---

[19] Fire Dynamics Simulator, an open-source, large-eddy simulation software for low-speed flows. FDS is developed and provided by the National Institute of Standards and Technology (NIST) of the United States Department of Commerce.
[20] Thunderhead Engineering, Manhattan, KS.
[21] NTSB Docket DCA16FP003 – Exemplar Mercury Regulator Test Report TR-2016-1.0 and Mercury Regulator Battery Test Report TR2017-1.0.

In Case 1 where the gas leakage was constant, and the water heater was not activated, the gas concentration began increasing until approaching a semi-steady state (Figure 5). In this case the meter room window was allowing natural gas to escape. In Case 2 with the intermittent leak and water heater activation the gas concentration would periodically increase and dissipate with an overall increasing trend in concentration (Figure 6). In this case the meter room window was allowing natural gas to escape when the water heater was inactive and then draw in fresh air when the water heater was active.

In order to make a comparison of this model to the closed form calculations the average concentration throughout the height of the room was calculated as a function of time. Figures 5 and 6 depict the temporal gas concentration at discreet levels across the height of the meter room for each case. Figures 5 and 6 also show the running average gas concentration across those levels as a function of time as well as a constant line representing the LEL. From these figures it can be seen that in Case 1 the average gas concentration reaches LEL in approximately 1 hour 52 minutes and in Case 2 the average gas concentration reaches LEL in approximately 2 hours 39 minutes.

A summary of the times required to reach an average LEL gas concentration in the meter room based on the lowest regulator failure vent leak flow rate are summarized in the table below.

Calculation	Natural gas leak rate (SCFH)	Water heater status	LEL	Time for the average gas concentration (floor to ceiling) to reach LEL (minute)
Closed form	165	Off	4.8%	67
CFD model	165	Off	4.8%	112
CFD model	165 (When water heater is off)	40 min off/ 20 min on	4.8%	159

These calculated times to reach an average LEL concentration throughout the room may not be the earliest time at which an explosion could take place. As the gas leak is ongoing, portions of the meter room atmosphere become explosive at different times. If an ignition source is present in an area that has reached LEL, an explosion can take place without requiring that the overall average concentration throughout the entire room reaches LEL. Figure 5 shows that in Case 1 the upper portion of the meter room, 48 inches above the floor, reaches LEL at approximately 59 minutes. Figure 6 shows that in Case 2 the upper portion of the meter room, 48 inches above the floor, reaches LEL at approximately 1 hour 28 minutes.

Michael Budinski
Chief, Materials Laboratory

Joseph Panagiotou
Senior Fire Protection Engineer

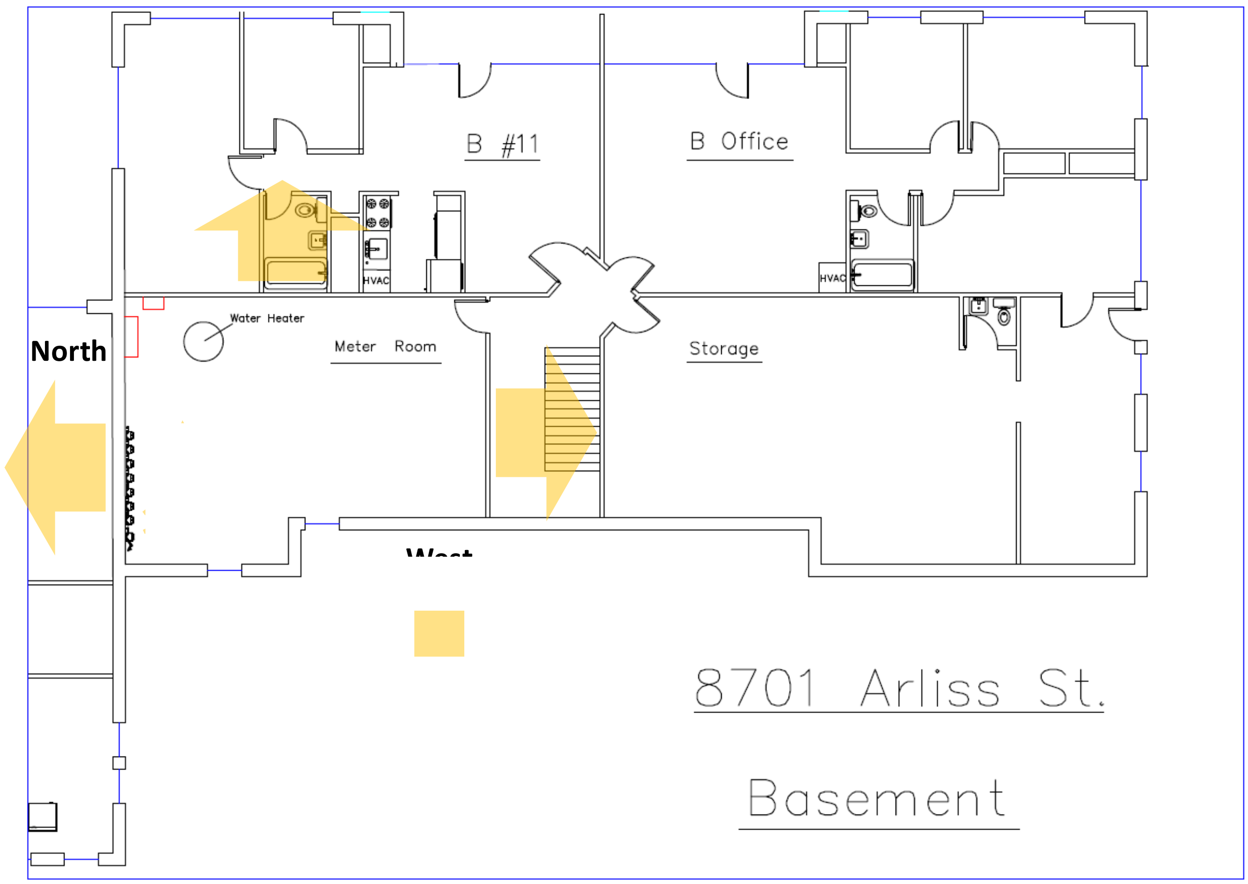

Figure 1 Plan-view diagram showing the configuration of the basement-level rooms at the 8701 Arliss Street apartment building and blast direction evidenced by building damage.

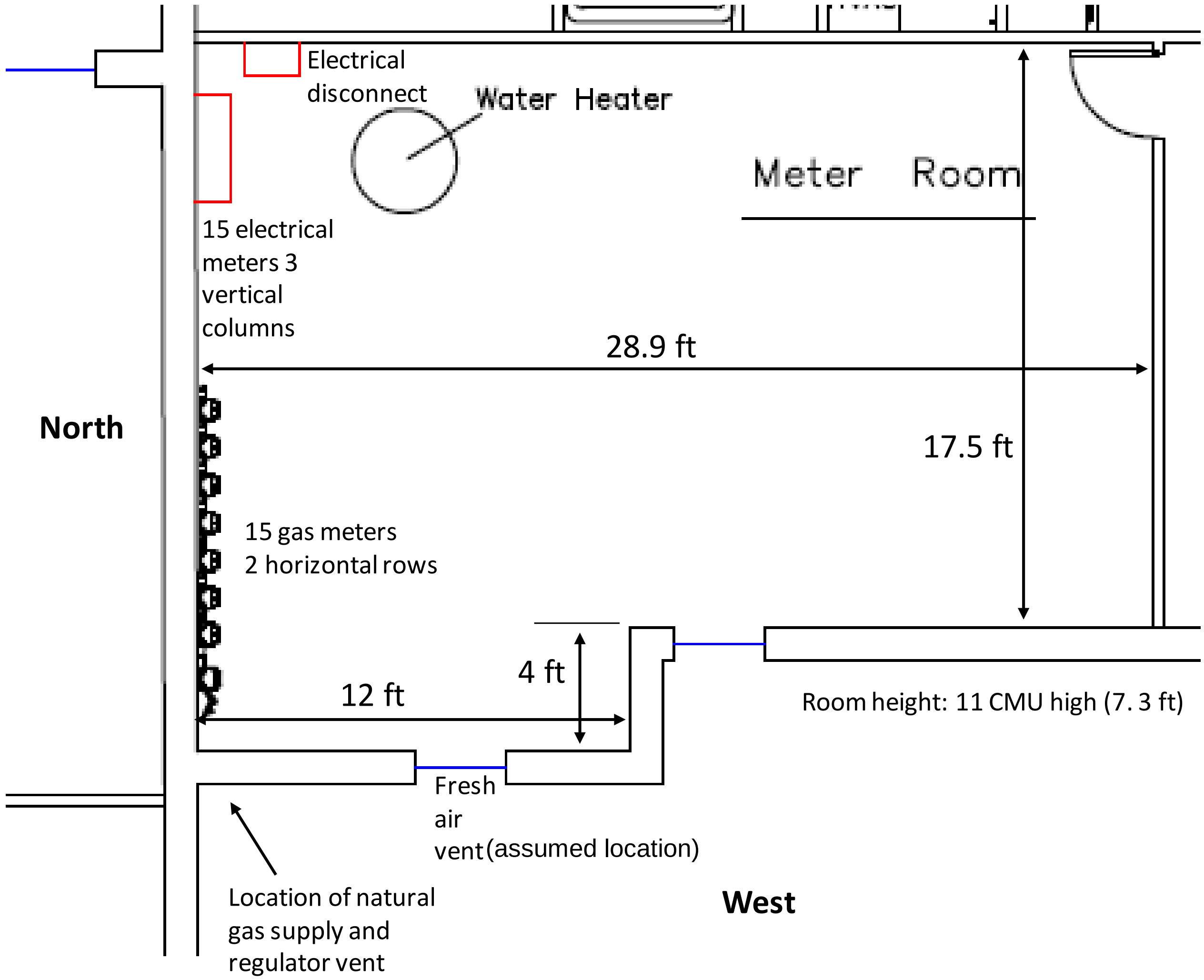

Figure 2 Plan-view diagram of the meter room in Building 8701 Arliss St. There were two windows in the room, one covered by glass, the other by wood with two holes. The drawing and dimensions are based on a Kay Management diagram and a laser survey by Washington Gas.

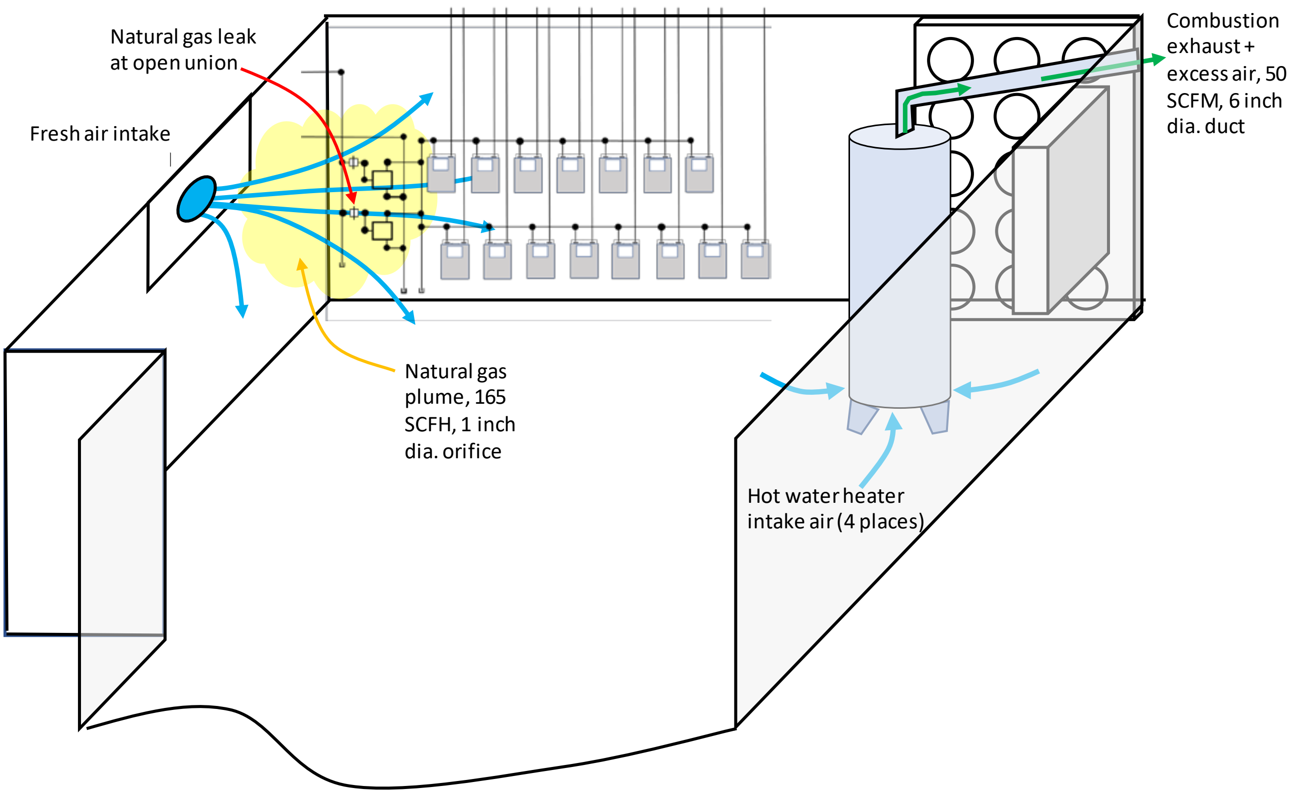

Figure 3 Three-dimensional visualization of the meter room, showing the arrangement of key utility items and the approximate flow of natural gas and air.

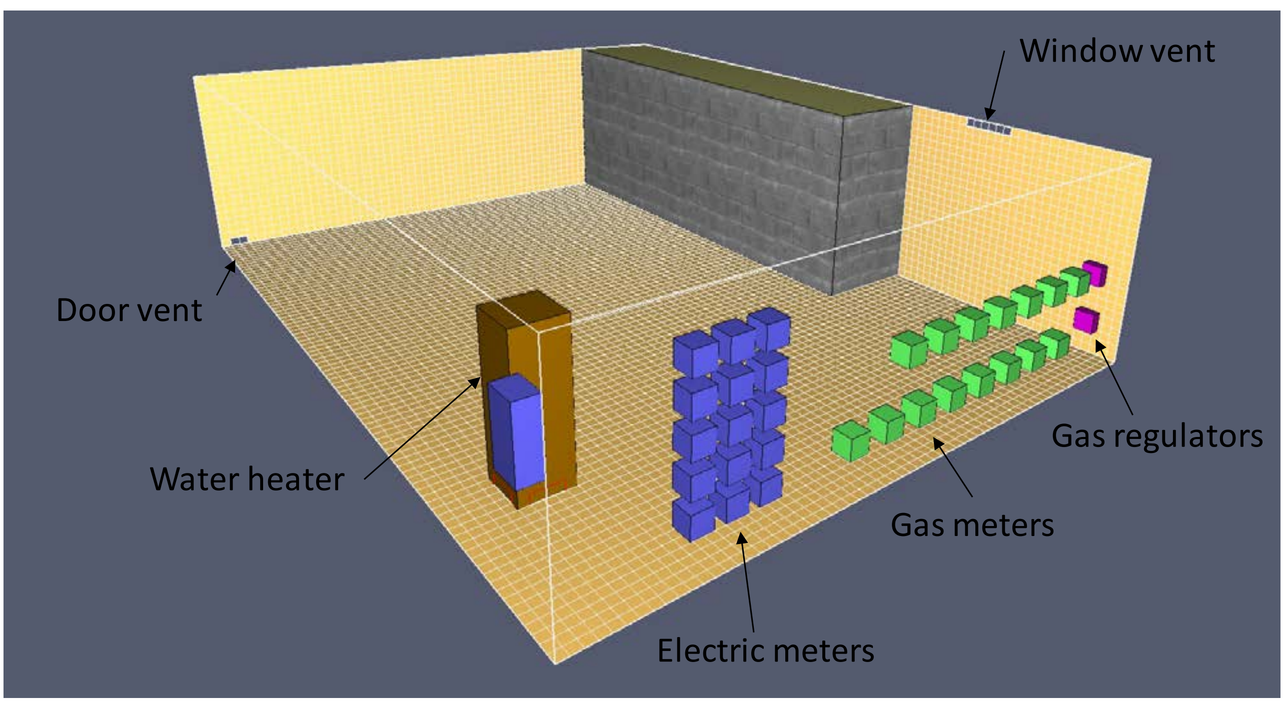

Figure 4 CFD computational domain with pertinent features labeled.

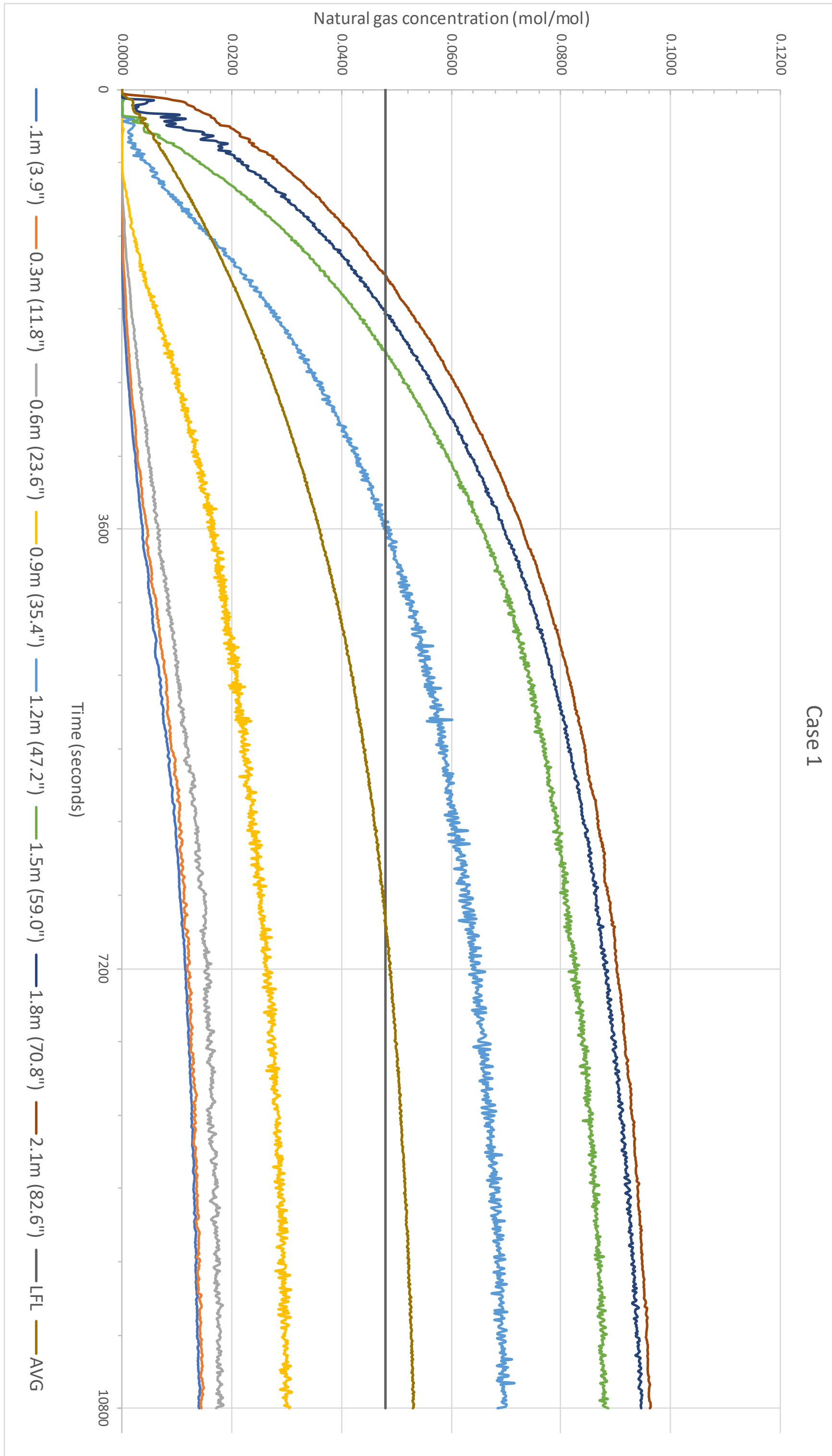

Figure 5 CFD model data output for Case 1—natural gas concentration at each measurement location as a function of time.

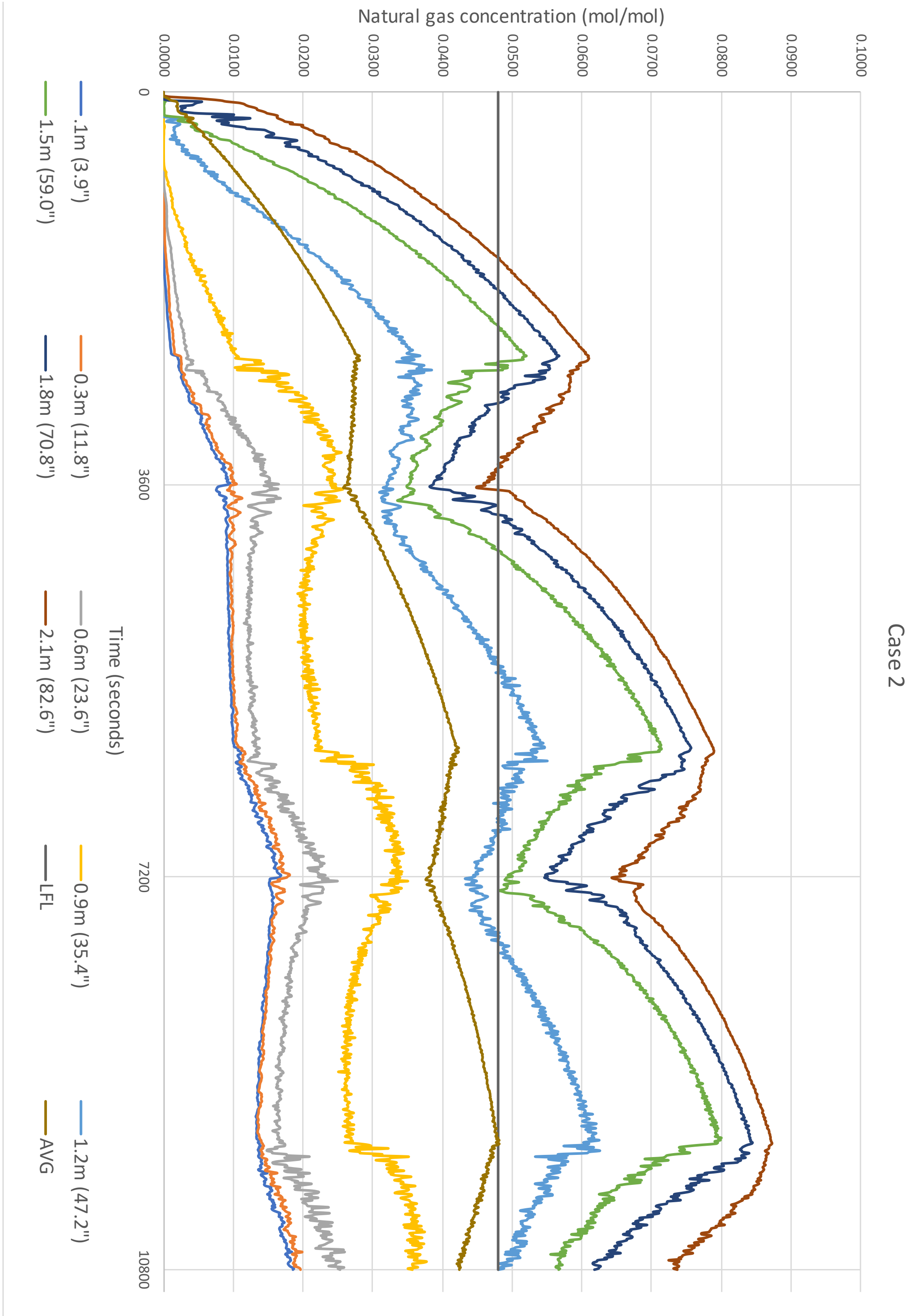

Figure 6 CFD model data output for Case 2—natural gas concentration at each measurement location as a function of time.