LBNL-6193E

Ernest Orlando Lawrence Berkeley National Laboratory

Predicting Backdrafting and Spillage for Natural-Draft Gas Combustion Appliances: Validating VENT-II

Vi H. Rapp, Albert Pastor-Perez, Brett C. Singer, and Craig P. Wray

Environmental Energy Technologies Division

April 2013

In Press as: Vi H. Rapp, Albert Pastor-Perez, Brett C. Singer, and Craig P. Wray. 2013. “Predicting Backdrafting and Spillage for Natural-Draft Gas Combustion Appliances: A Validation of VENT-II”. HVAC&R Research, DOI:10.1080/10789669.2013.771948

DISCLAIMER

LEGAL NOTICE

ACKNOWLEDGMENTS

This work was supported by the California Energy Commission through Contract 500-10-052. Additionally, this work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under Contract No. DE AC02-05CH11231.

The authors thank the Pacific Gas and Electric Company (PG&E) for providing access to their test house in Stockton, CA; David Grimsrud for providing insights about unpublished performance data regarding the Minnesota test house; and Paul Glanville at the Gas Technology Institute (GTI) for providing VENT-II technical support. We also thank Kristina Hamachi LaCommare for her assistance as Project Contract Manager at Berkeley Lab.

ABSTRACT

VENT-II is a computer program designed to provide detailed analysis of natural draft and induced draft combustion appliance vent-systems (i.e., furnace or water heater). This program is capable of predicting house depressurization thresholds that lead to backdrafting and spillage of combustion appliances; however, validation reports of the program being applied for this purpose are not readily available. The purpose of this report is to assess VENT-II's ability to predict combustion gas spillage events due to house depressurization by comparing VENT-II simulated results with experimental data for four appliance configurations.

The results show that VENT-II correctly predicts depressurizations resulting in spillage for natural draft appliances operating in cold and mild outdoor conditions, but not for hot conditions. In the latter case, the predicted depressurizations depend on whether the vent section is defined as part of the vent connector or the common vent when setting up the model. Overall, the VENT-II solver requires further investigation before it can be used reliably to predict spillage caused by depressurization over a full year of weather conditions, especially where hot conditions occur.

TABLE OF CONTENTS

ACRONYMS AND SYMBOLS

ANSI	American National Standards Institute
APT	Automatic Performance Testing
BPI	Building Performance Institute
CAZ	Combustion Appliance Zone
CO	Carbon monoxide
GRI	Gas Research Institute
GTI	Gas Technology Institute
H	Height of the vent section
HVAC	Heating, Ventilating, and Air-Conditioning
NFPA	National Fire Protection Association
Ns	Total number of sections in the vent connector or common vent
in.Hg	inches of mercury
in.w.c.	inches water column
Δp	Pressure differential (Pa)
$\bar{\rho}_i$	Mean density of vent gas in vent section i
ρ_0	Density of air outside the vent at the elevation of the vent section
PG&E	Pacific Gas and Electric Company
USB	Universal Serial Bus

1. INTRODUCTION

VENT-II is a computer program that was developed for analyzing the performance of a vent system serving one or two natural-draft gas appliances or the single vent serving a fan-assisted appliance (Detty et al. 1998, Rutz et al. 1992). It has been used to generate the current vent sizing tables in the National Fuel Gas Code (NFPA 2012), which is referred to by U.S. building codes and standards. VENT-II is also cited in the ASHRAE Handbook – HVAC Systems and Equipment as a tool for analyzing chimney performance and steady-state chimney design (ASHRAE 2012).

The program calculates temperatures, pressures, flows, and flue gas condensation for each section of the vent system. These calculations are based on classical fluid flow, heat transfer, and mass transfer theory, and include phenomena such as external natural convection, internal forced and natural convection, mass transfer of water vapor between the vent gas and the vent wall, condensation heat transfer, heat transfer through the vent wall, available draft, mass flow, and pressure loss. Vent system performance parameters are calculated as a function of time. The transient (time-varying) calculation is especially necessary to represent startup dynamics and for determining condensation inside the vent system. The time step in VENT-II is fixed at 5 seconds (Rutz et al. 1992).

The available draft, or pressure drop, in the vent system is calculated by summing the pressure difference across each section in the vent system:

$$\mathrm{Draft} = \sum_{i=1}^{Ns} \Delta P_i \tag{1}$$

where i is the vent section, N_s is the total number of vent sections, and ΔP_i is the total pressure difference across each vent section. The total pressure difference across each vent section is calculated using:

$$\Delta P_i = (\rho_0 - \bar{\rho}_i) g H_i \tag{2}$$

where ρ_0 is the outdoor-air density (kg/m^3), $\bar{\rho}_i$ is the mean gas density in vent section i (kg/m^3), g is the gravitational constant (9.81 m/s^2 or 32.2 ft/s^2), and H_i is the vent height of section i (m). The ideal gas law is used for calculating the vent gas density, such that the mean density in each vent section is inversely proportional to the mean vent gas temperature.

VENT-II's temperature, pressure, flow, and condensation predictions reportedly have been validated for a variety of vent systems (Glanville et al. 2011, Rutz et al. 1992, Rutz and Leslie 1993). These validation reports, however, are not readily available and do not clearly address the program's ability to predict combustion appliance zone (CAZ) depressurizations that lead to combustion gas spillage into the CAZ. This ability is important because it can define a key vent system characteristic that, when combined with separate knowledge about CAZ depressurization and indoor combustion gas concentration statistics (magnitude and frequency), can determine whether a vent system can operate safely (Rapp et al. 2012). The purpose of this report is to validate whether VENT-II can be used to predict combustion appliance zone depressurizations that lead to spillage.

Following this introduction, we provide a detailed description for differentiating between backdrafting and spillage using VENT-II. Next, we describe the simulation and experimental setup for each vent system that we considered: four appliance and vent system configurations, each with a different set of outdoor temperature conditions (cold, mild, or hot). Then, we present and analyze the results. In the final section, we provide conclusions and recommendations.

2. IDENTIFYING SPILLAGE EVENTS IN VENT-II

Experimental research has shown that simply measuring or predicting static pressure at the vent entry relative to the CAZ pressure can be misleading when attempting to identify spillage events (Grimsrud and Hadlich 1999; Koontz et al. 1999, Koontz et al. 2001, Nagda et al. 2002). For example, an appliance with an undersized vent system can have a negative static pressure in the vent relative to the CAZ, indicating the appliance is drafting, and yet still spill exhaust gases into the living space. Spillage occurs because the vent capacity limits the amount of dilution air and exhaust gases flowing through the vent system.

To illustrate this case, we used VENT-II to simulate venting for two appliances: a 40 kBtu/hr (11.7 kW) appliance with an appropriately sized vent system and a 120 kBtu/hr (35.2 kW) appliance with a vent system sized for a 40 kBtu/hr (11.7 kW) appliance (NFPA 2012). As expected, the pressure in the vent for both appliance simulations was negative, as shown in Figure 1, indicating that the appliance is drafting.

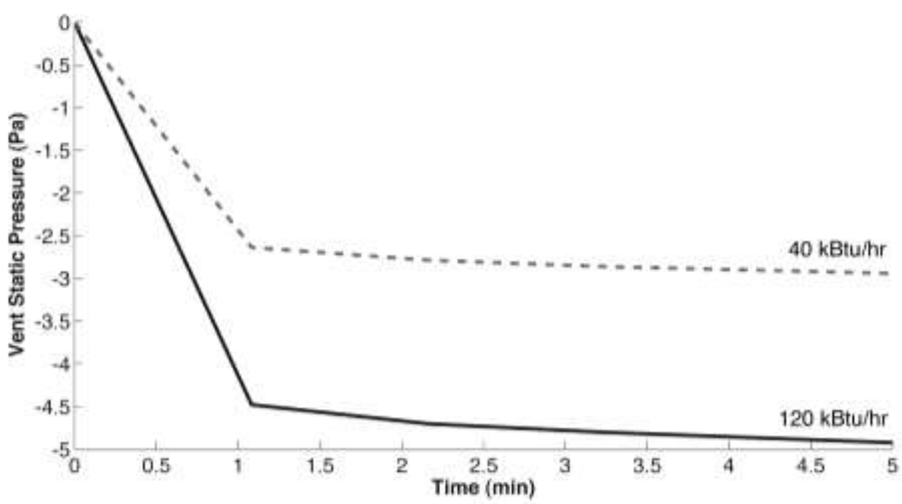
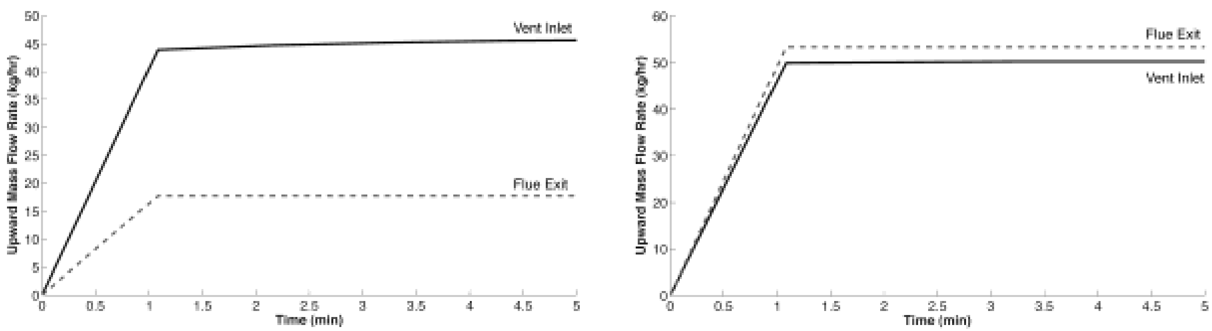


Figure 1: Vent static pressure remains negative in the vent system when the appliance is appropriately sized (40 kBtu/hr or 11.7 kW) and when the appliance is oversized (120 kBtu/hr or 35.2 kW), even though the oversized appliance spills combustion gases into the living space, as shown in Figure 2.

For the 40 kBtu/hr (11.7 kW) appliance, Figure 2(A) shows that mass is gained from the flue outlet to the vent inlet, which indicates that dilution air is entering the vent and spillage is not occurring. However, Figure 2(B) shows that mass is lost between the flue outlet and vent inlet for the 120 kBtu/hr (35.2 kW) appliance, which indicates that the appliance is spilling. In this report, we assumed that simulated vent systems with a loss in mass between the flue and vent are spilling and we used simulated vent static pressure to indicate if the appliance was drafting (negative vent static pressure) or backdrafting (positive vent static pressure).



(A) 40 kBtu/hr Appliance   (B) 120 kBtu/hr Appliance

Figure 2: For a 40 kBtu/hr appliance with an appropriately sized vent system (A), the mass flow rate of gases at the flue outlet is less than the mass flow rate of gases in the vent, which indicates that dilution air is entering the vent and the appliance is not spilling. However, for an oversized 120 kBtu/hr (35.2 kW) appliance using the same vent system sized for a 40 kBtu/hr (11.7 kW) appliance (B), the mass flow rate of gases at the flue outlet is greater than the mass flow rate of gases in the vent, which indicates that the appliance is spilling.

3. SIMULATION AND EXPERIMENTAL SETUP

We assessed VENT-II's ability to predict combustion gas spillage events due to house depressurization by comparing VENT-II simulated results with experimental data (vent static pressure during baseline conditions and CAZ depressurization resulting in spillage) for four appliance-vent systems. These systems included:

- a common-vented water heater and furnace system located in Twin Cities, Minnesota;
- a single-vented orphaned water heater located in Berkeley, California;
- a single-vented orphaned water heater located in Stockton, California; and
- a single-vented wall furnace located in Stockton, California.

As described in Section 3.1, experimental data for the system in Twin Cities, Minnesota were taken from a report written by Grimsrud and Hadlich (1995). For the other three systems, we collected the performance data. The remainder of this section provides a detailed description of each vent system and describes the other data that we used or collected to model each system.

3.1 Central Furnace and Water Heater in Twin Cities, Minnesota

Grimsrud and Hadlich (1995) developed and field tested a protocol that evaluates the impact of house depressurization on backdrafting and spillage of naturally-vented combustion appliances. They found that three of the ten homes that they tested were spillage prone. One of these three homes had a common-vented natural-draft furnace and natural-draft water heater vent system (located in Twin Cities, Minnesota and titled EP2 in their report) and enough information was provided in their report so that we could simulate the vent system using VENT-II.

According to the report: “The water heater vent connector is a 4 inch (10.16 cm) diameter duct with two 90º elbows before the drip-T. The furnace vent connector is 6 inch (15.24 cm) diameter with three 45º elbows before the drip-T. After the drip-T, the vent has two 45º elbows. A section of the vent runs diagonally through the garage before exiting vertically through the garage roof” The lengths of each individual vent section were not provided, but dimensions of the basement, first floor, and second floor were given. Using these floor dimensions, we approximated the length of each vent section. It should be noted that changing lengths of the runs by 1 foot (30.48 cm) had no effect on simulated drafting and spillage results. Figure 3 shows a schematic of the common-vented appliances that we modeled in VENT-II. Table 1 provides the appliance ratings and operating conditions for the furnace and the water heater.

Table 1: Appliance ratings and operating conditions for the common-vented natural-draft furnace and water heater system located in Twin Cities, Minnesota (EP2) (Grimsrud & Hadlich 1995).

Indoor Temperature °C (°F)	Outdoor Temperature °C (°F)	Outdoor Relative Humidity %	Excess Combustion Air for Both Appliances %	Barometric Pressure kPa (in. Hg)	Furnace Input Rating kW (kBtu/hr)	Water Heater Input Rating kW (kBtu/hr)
20 (68)	-1 (30)	22	30	101 (29.9)	36.6 (125)	11.7 (40)

Grimsrud and Hadlich performed 4 minute long spillage tests at three combustion appliance zone (CAZ) pressures with respect to outdoors: a baseline pressure (no exhaust appliances operating) of -2.5 Pa (-0.010 in.w.c.), -7.5 Pa (-0.030 in.w.c.), and -9.0 Pa (-0.036 in.w.c.). The CAZ was initially depressurized by operating the range hood and then further depressurized by operating both the range hood and the dryer. For each spillage test, they reported the CAZ depressurization and whether the appliance was backdrafting and spilling or drafting and not spilling. Differential vent pressure, which was measured at the base of the common vent, was recorded only for the baseline pressure condition, -2.5 Pa (-0.010 in.w.c.).

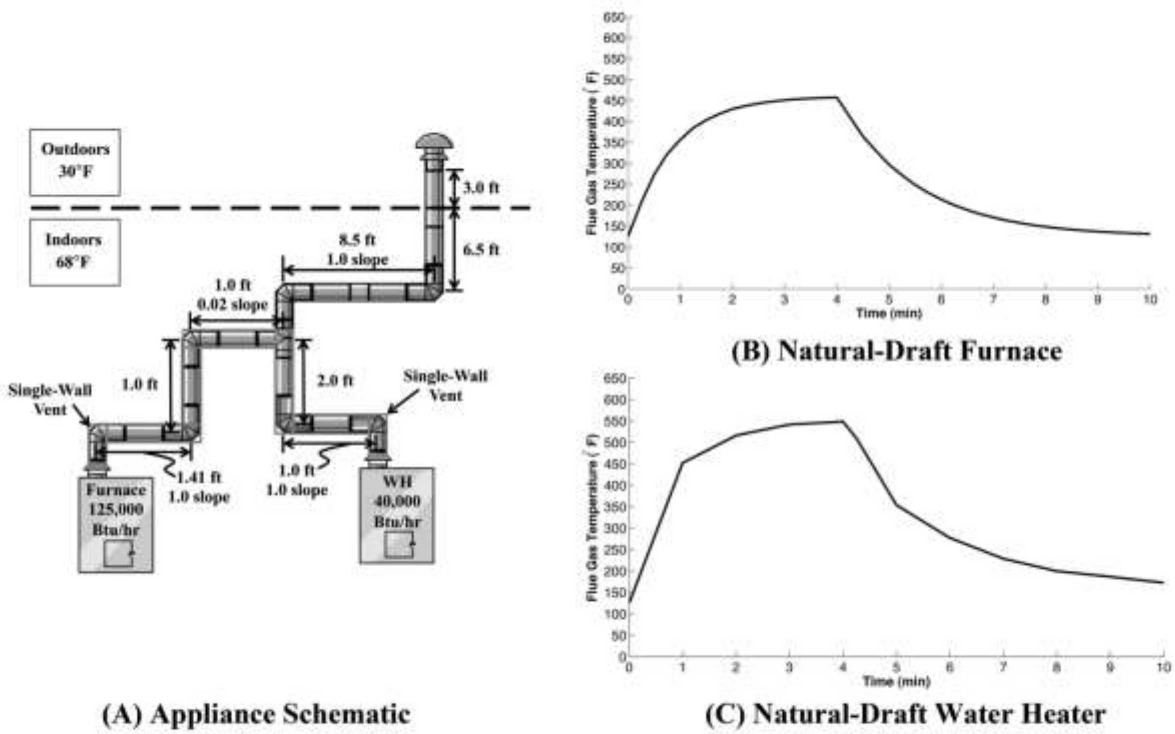


Figure 3: Schematic of furnace and water heater vent system in Twin Cities, MN as modeled in VENT-II (A) and the simulated flue gas temperature for the furnace (B) and the water heater (C) during one operating cycle. The furnace vent connector is composed of two, 6 in. (15.24 cm) diameter single-walled vents. The water heater (WH) vent is composed of two circular, 4 in. (10.16 cm) diameter single-walled vents. The common vent contains four circular, 6 in. (15.24 cm) diameter B-vents. Horizontal sections with slopes greater than or equal to 1.0 are assumed to have 45-degree elbows. Horizontal sections with slopes less than 1.0 are assumed to have 90-degree elbows.

Grimsrud and Hadlich did not provide appliance flue temperature profiles for the natural draft furnace and water heater, but they did state that each appliance was operated for 4 minutes. To model this common vented system in VENT-II, we used the program’s default natural draft furnace flue temperature profile to approximate the furnace and reduced the firing time to 4 minutes. We used the flue temperature profile from the orphaned water heater in Stockton, California to approximate the water heater in Grimsrud and Hadlich’s report. This profile was chosen because the age of the water heater closely matched the age of the water heater in their report. We adjusted the firing time of the temperature profile from 12 minutes to 4 minutes in the model to match the firing time listed in their report. The modeled flue gas temperature profiles for the furnace and the water heater are also shown in Figure 3.

3.2 Water Heater in Berkeley, California

This 1907 two-story Berkeley, California home contains an orphaned water heater located in the laundry room on the first floor. A schematic of the water heater, as modeled in VENT-II, is shown Figure 4. We expected that this system would be susceptible to spillage at low house depressurizations because the vent system contains two runs with 90-degree elbows and one of the runs does not meet the National Fuel Gas Code minimum slope requirement (1/4 inch or 6.35 mm, per horizontal foot). Table 2 provides the appliance rating and operating conditions.

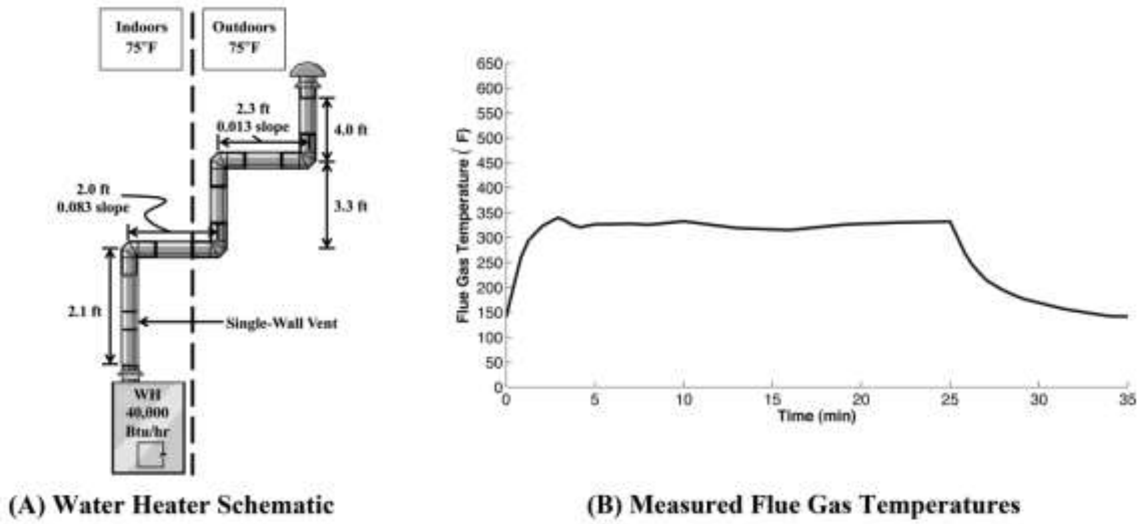


Figure 4: Schematic of the vent system modeled in VENT-II (A) and the measured flue gas temperatures (B) of the orphaned water heater located in Berkeley, CA. The vent connector is composed of two circular, 3-in. (7.62 cm) diameter single-walled vents. The common vent contains four circular, 3-in. (7.62 cm) diameter B-vents. All elbows are 90-degrees.

Table 2:Appliance rating and operating conditions for the natural draft water heater system located in Berkeley, CA.

Indoor Temperature °C (°F)	Outdoor Temperature °C (°F)	Outdoor Relative Humidity %	Excess Combustion Air %	Barometric Pressure kPa (in.Hg)	Water Heater Input Rating kW (kBtu/hr)
24 (75)	24 (75)	55	33	100 (29.5)	11.7 (40)

Following the protocols outlined in the National Fuel Gas Code (NFPA 2012) and the Whole House Combustion Safety Test Procedure (PG&E 2011), we conducted a "draft test" at three CAZ pressures relative to outdoors: baseline of 0.0 Pa, -2.0 Pa (-0.008 in.w.c.), and -3.0 Pa (-0.012 in.w.c.). For the "draft test", we used a smoke pen to identify whether spillage was occurring 5 minutes after appliance start-up. Exterior doors and windows remained closed for the duration of the test while interior doors remained open. A blower door was used to depressurize the CAZ until upward flow in the vent could not be established within 5 minutes. The vent system was allowed to cool to ambient conditions between depressurized “draft tests”.

To fully characterize the vent system in VENT-II, we also measured the following: barometric pressure, CAZ depressurization with respect to outdoors, vent temperature and static pressure with respect to the CAZ (measured 1 ft., 30.48 cm, above the draft diverter as recommended by BPI (2012), CAZ temperature, outdoor temperature, flue temperature, excess combustion air, percent excess air in the flue, and carbon monoxide (CO) concentration in the flue. Vent static pressure was monitored only at the baseline CAZ pressure because when the CAZ was depressurized, vent static pressures fluctuated greatly and a meaningful measurement could not be obtained. Prior to depressurizing the house, we measured the flue gas temperature each minute for a complete operating cycle as shown in Figure 4, ensuring that the appliance reached a steady state flue gas temperature before the burner was turned off. If spillage occurred, we measured its duration using a smoke pen for up to 5 minutes before the appliance was shut-off.

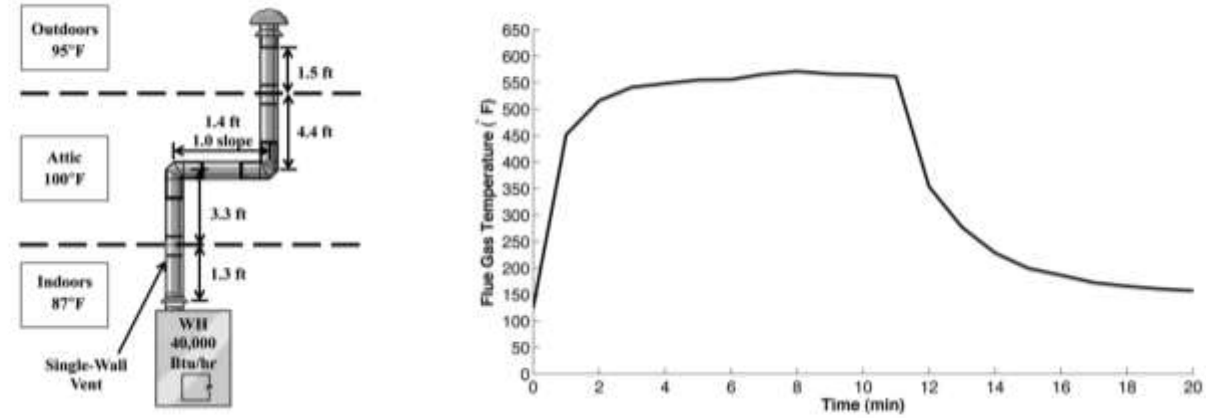
An Energy Conservatory Automatic Performance Testing (APT) System connected to a computer was used to measure differential pressures and indoor and outdoor air temperatures. A Testo 327-1 Combustion Analyzer Kit was used to measure flue temperature, vent temperature, excess air in the flue, and carbon monoxide in the flue. Barometric pressure was measured using a Gulf Coast Data Concepts B1100-1 USB Data Logger. Outdoor relative humidity and wind speed were obtained from a local weather station.

3.3 Water Heater and Wall Furnace at the PG&E Test House in Stockton, California

The Pacific Gas and Electric Company (PG&E) test house is a single-story building with an attic located at their Energy Training Center in Stockton, CA. The purpose of the training center is to provide continuing education for businesses, construction professionals, and participants of energy efficiency education programs. We chose this house for testing because it contains several appliances, among which are an orphaned water heater and a wall furnace, and it could be used during hot weather conditions.

3.3.1 Water Heater

The water heater is located in the laundry room adjacent to the kitchen. A door can be closed to separate the laundry room from the kitchen, but this door remained open during the duration of our test so that the CAZ could be depressurized directly using a blower door. A schematic of the VENT-II model for the water heater is shown in Figure 5. Table 3 provides the appliance rating and operating conditions. The same test procedures and measurements conducted in the Berkeley, California home were also conducted on the orphaned water heater in Stockton, California. Figure 5 also shows the measured flue temperature profile for the water heater during one operating cycle. The “draft test” (assessing whether spillage was occurring five minutes after appliance start-up) was conducted at four CAZ pressures relative to outdoors: baseline of 0.0 Pa, -5.5 Pa (-0.022 in.w.c.), -9.0 Pa (-0.036 in.w.c.), and -11.0 Pa (-0.044 in.w.c.).



(A) Water Heater Schematic **(B) Measured Flue Gas Temperatures**

Figure 5: Schematic of the vent system modeled in VENT-II (A) and the measured flue gas temperatures (B) of the orphaned water heater at the PG&E Test House in Stockton, CA. The vent connector is composed of one circular, 3-in. (7.62 cm) diameter single-walled vent and three circular, 3-in. (7.62 cm) diameter B-vents. The common vent contains one circular, 3-in. (7.62 cm) diameter B-vent. The elbows are 45-degrees.

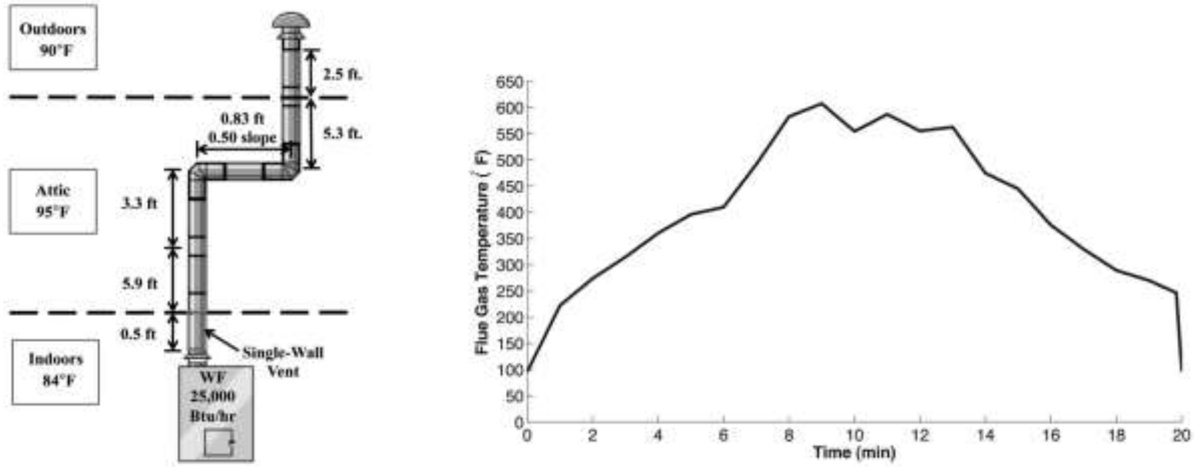
Table 3:Appliance rating and operating conditions for the natural-draft water heater system located in Stockton, CA.

T_{CAZ} °C (°F)	T_{out} °C (°F)	T_{attic} °C (°F)	Outdoor Relative Humidity %	Excess Combustion Air %	Barometric Pressure kPa (in.Hg)	Water Heater Input Rating kW (kBtu/hr)
31 (87)	35 (95)	38 (100)	13	30	100 (29.6)	11.7 (40)

3.3.2 Wall Furnace

We also conducted a “draft test” on the wall furnace located in the living room, even though operation of the wall furnace during summer conditions is unlikely. The purpose of this test was to determine VENT-II’s ability to predict drafting and spillage in a vent system that changes shape. For this furnace, the vent is square just after the draft diverter, then connects to an oval vent and finally to a circular vent. A schematic of the wall furnace modeled in VENT-II is shown in Figure 6. Table 4 provides the appliance rating and operating conditions. The same procedures conducted for the orphaned water heater in Berkeley, California were used for the wall furnace. Figure 6 also shows the measured wall furnace flue temperature profile for one operating cycle.

The “draft test” was conducted at three CAZ pressures relative to outdoors: baseline of 1.5 Pa (0.006 in.w.c.), -9.0 Pa (-0.036 in.w.c.), and -12.0 Pa (-0.048 in.w.c.).



(A) Wall Furnace Schematic   (B) Measured Flue Gas Temperatures

Figure 6: Schematic the vent system modeled in VENT-II (A) and the measured flue gas temperatures (B) of the wall furnace at the PG&E Test House in Stockton, CA. The vent connector is composed of a single-wall rectangular vent, 1-in. (2.54 cm) x 4.5-in. (11.43 cm), an oval B-vent, 2-in. (5.08 cm) x 7-in. (17.78 cm), and two circular, 4-in. (10.16 cm) diameter B-vents. The common vent contains four circular, 4-in. (10.16 cm) diameter B-vents. The elbows are 90-degrees.

Table 4: Appliance rating and operating conditions for the natural-draft wall furnace system located in Stockton, CA.

T_{CAZ} °C (°F)	T_{out} °C (°F)	T_{Attic} °C (°F)	Relative Humidity %	Excess Combustion Air %	Barometric Pressure kPa (in.Hg)	Water Heater Input Rating kW (kBtu/hr)
30 (86)	32 (90)	35 (95)	26	30	101 (29.9)	7.3 (25)

4. RESULTS AND DISCUSSION

To determine whether VENT-II can be used to predict CAZ depressurizations leading to five minutes of continuous combustion appliance spillage (spillage depressurization), we compared simulated results with experimental data for four appliance configurations and three outdoor temperature conditions. We found that VENT-II accurately predicts spillage for appliances operating in cold and mild conditions, but had difficulty predicting spillage for appliances in hot conditions. Following the comparison of simulated and experimental results, we describe simulation problems that we encountered.

4.1 Depressurization-Induced Spillage

For each VENT-II simulation, an appliance was considered to spill when mass was being lost to indoors at the draft diverter (i.e., when the predicted mass flow of exhaust gas in the vent was less than the mass flow of exhaust gas leaving the flue). Similar to the experimental results, spillage events lasting five or more minutes in the simulation were considered to fail the National Fuel Gas Code “draft test” (NFPA 2012). As described in Section 2.0, vent static pressure with respect to the CAZ was not used as an indicator of spillage because an appliance can have a negative vent static pressure and still spill (i.e., for undersized vents). Instead, vent static pressure was only used to determine whether the appliance was backdrafting (downward flow) or drafting (upward flow). For the baseline CAZ pressure case (no exhaust appliances operating), we compared the simulated vent static pressure with experimental results.

4.1.1 Spillage Depressurization for Common Vented System in Twin Cities, Minnesota

Grimsrud and Hadlich (1995) tested the common-vented furnace and water heater located in Twin Cities, MN for spillage, independently, during winter conditions. Their experimental results showed that the flow in the furnace vent was upward at the baseline CAZ pressure of -2.5 Pa (-0.010 in.w.c.) relative to outdoors and there was no spillage. When the CAZ pressure was -7.5 Pa (-0.030 in.w.c.), the furnace spilled for 90 seconds before establishing upward flow. At a CAZ pressure of -9.0 Pa (-0.036 in.w.c.), the furnace spilled for the duration of the test (4 minutes). The water heater, which was tested when the CAZ pressure was -7.5 Pa (-0.030 in.w.c.), spilled during the 4 minutes of testing.

In general, the VENT-II results agree well with the experimental results, as shown in Table 5. Figure 7 shows that VENT-II predicted that the furnace will backdraft and spill for about 10 seconds before establishing upward draft when the CAZ pressure is -7.5 Pa. When the CAZ pressure is -9.0 Pa, VENT-II predicted that the furnace will spill for the duration of the test (4 minutes). Figure 8 shows that VENT-II predicted that the water heater will backdraft and spill for the duration of the test when the CAZ pressure is -7.5 Pa. Although VENT-II could predict whether depressurization-induced spillage would occur for the furnace and water heater at each pressure condition, the predicted vent static pressure for the furnace under baseline conditions (-2.7 Pa, -0.011 in.w.c.) was almost twice the measured value (-1.5 Pa, -0.006 in.w.c.). Additionally, the predicted spillage time for the furnace at the -7.5 Pa CAZ pressure was 80 seconds shorter than that measured.

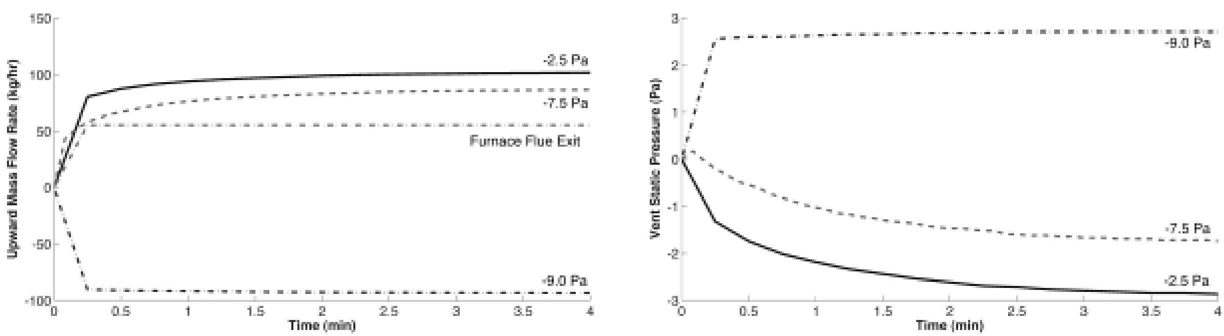
Much like the experimental data, VENT-II predicted that the spillage depressurization for the furnace was between -7.5 Pa and -9.0. However, the exact spillage depressurization could not be determined using VENT-II because it continuously gave a computational error at depressurizations between -7.5 Pa and -8.5 Pa (-0.030 and -0.034 in.w.c.). At -8.5 Pa, VENT-II predicted the appliance would spill for 4 minutes. The solver error associated with VENT-II is discussed further in Section 4.2.2.

Table 5: Measured and simulated spillage states and vent static pressures for natural-draft appliances located in Twin Cities, MN during winter conditions.

Appliance	CAZ Pressure Pa (in.w.c.)	State* (Spill / No Spill)		Vent Static Pressure Pa (in.w.c.)	
		Measured	VENT-II	Measured	VENT-II**
Furnace	-2.5 (-0.010)	No Spill	No Spill	-1.5 (-0.006)	-2.7 (-0.011)
Furnace	-7.5 (-0.030)	90 sec. Spill	10 sec. Spill	N/A	-1.7 (-0.007)
Water Heater	-7.5 (-0.030)	Spill	Spill	N/A	2.2 (0.009)
Furnace	-9.0 (-0.036)	Spill	Spill	N/A	2.7 (0.011)

* "Spill" indicates that the appliance spilled exhaust gases into the CAZ for the duration of the test (4 minutes). A time (i.e., 90 seconds) indicates that the appliance initially spilled for that duration and then did not spill for the remainder of the test. "No Spill" indicates that the appliance did not spill at any time.

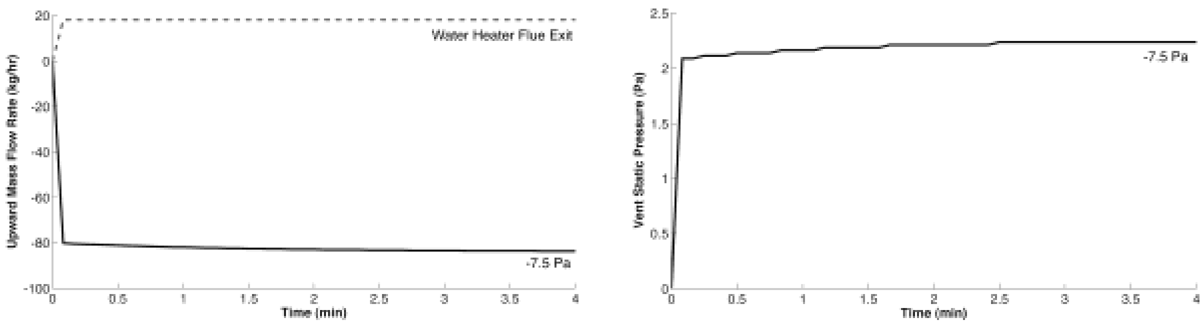
** Vent static pressure 4 minutes after appliance start-up.



(A) Upward Mass Flow Rate

(B) Vent Static Pressure

Figure 7: VENT-II predicted that the common-vented furnace located in Twin Cities, MN will spill (A) and backdraft (B) for the duration of the test (4 minutes) when the CAZ pressure, with respect to outdoors, is -9.0 Pa (-0.036 in.w.c.). When the CAZ pressure is -7.5 Pa (-0.030 in.w.c.), VENT-II predicted that the appliance will backdraft for about 10 seconds before establishing upward draft but would not spill. No spillage or backdrafting was predicted at a CAZ pressure of -2.5 Pa (-0.010 in.w.c.).



(A) Upward Mass Flow Rate **(B) Vent Static Pressure**

Figure 8: VENT-II predicted that the common-vented water heater located in Twin Cities, MN will spill (A) and backdraft (B) for the duration of the test (4 minutes) when the CAZ pressure, with respect to outdoors, is -7.5 Pa (-0.030 in.w.c.).

4.1.2 Spillage Depressurization for the Orphaned Water Heater in Berkeley, California

We tested the orphaned water heater located in Berkeley, CA for spillage during summer conditions. It should be noted that summer conditions in Berkeley are similar to spring or fall conditions in most other parts of the United States, given that the outdoor temperature (75°F) was the same as the indoor temperature. Our experiments showed that, for baseline conditions (0.0 Pa), the water heater drafted upward and there was no spillage. When the CAZ pressure was -2.0 Pa (-0.008 in.w.c.), the water heater fluctuated between spilling and no spilling for the duration of the test. When the CAZ pressure was -3.0 Pa (-0.012 in.w.c.), the water heater spilled continuously.

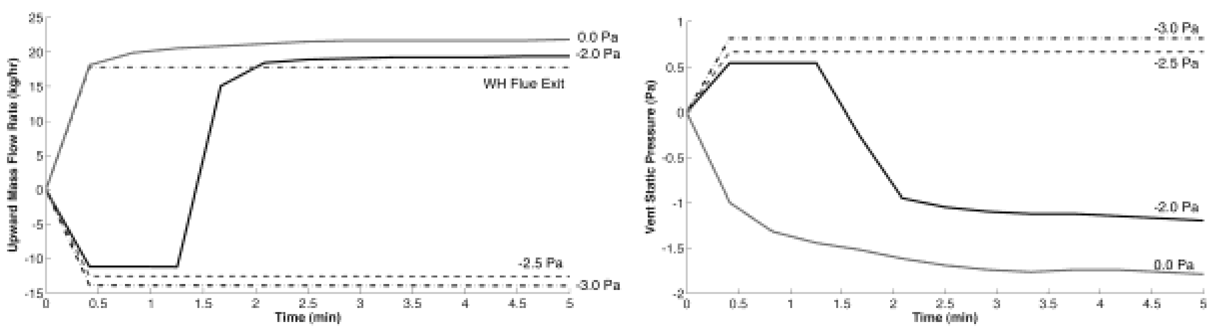
The simulated results from VENT-II show good agreement with the experimental results for this appliance (Table 6). For the baseline CAZ pressure, VENT-II results match experimental data: it predicted a vent static pressure of -1.8 Pa (-0.007 in.w.c.), and that the appliance will draft upward and not spill. However, when the CAZ pressure was -2.0 Pa, Figure 9 shows that VENT-II predicted that the appliance will spill for almost 2 minutes. For the appliance to spill for the duration of the test (5 minutes), VENT-II predicted that the CAZ pressure should be -2.5 Pa (-0.010 in.w.c.), while experimental results indicate -3.0 Pa (-0.012 in.w.c.). Figure 9 also shows that backdrafting coincided with the spillage events.

Table 6: Measured and simulated spillage states and vent static pressures for the orphaned water heater in Berkeley, CA during summer conditions.

CAZ Pressure	State* (Spill / No Spill)		Vent Static Pressure Pa (in.w.c.)	
Pa (in.w.c.)	Measured	VENT-II	Measured	VENT-II**
0.0 (0.0)	No Spill	No Spill	-1.8 (-0.007)	-1.8 (-0.007)
-2.0 (-0.008)	Fluctuating Spill	2 min. Spill	N/A	-1.2 (-0.005)
-3.0 (-0.012)	Spill	Spill	N/A	0.7 (0.003)

* "Spill" indicates that the appliance spilled exhaust gases into the CAZ for the duration of the test (5 minutes). A time (i.e., 2 minutes) indicates that the appliance initially spilled for that duration and then did not spill for the remainder of the test. "Fluctuating Spill" indicates that the appliance fluctuated between spilling and not spilling for the duration of the test. "No Spill" indicates the appliance did not spill at any time.

** Vent static pressure 5 minutes after appliance start-up.



(A) Upward Mass Flow Rate **(B) Vent Static Pressure**

Figure 9: VENT-II predicted that the orphaned water heater located in Berkeley, CA will spill (A) and backdraft (B) for the duration of the test (5 minutes) when the CAZ pressure, with respect to outdoors, is less than or equal to -2.5 Pa (-0.010 in.w.c.). The water heater was also predicted to spill and backdraft for almost 2 minutes before establishing upward flow when the CAZ pressure was -2.0 Pa (-0.008 in.w.c.).

4.1.3 Spillage Depressurization for the Orphaned Water Heater in Stockton, California

We tested the orphaned water heater located in Stockton, CA for spillage during summer conditions. The water heater drafted upward and did not spill at the baseline CAZ pressure (0.0 Pa) or when the CAZ pressure was -5.5 Pa (0.022 in.w.c.) relative to outdoors. When the

CAZ pressure reached -9.0 Pa (-0.036 in.w.c.), the water heater fluctuated between spilling and not spilling for the 5 minute duration of the test. When the CAZ pressure was -11.0 Pa (-0.044 in.w.c.), the water heater spilled continuously for the duration of the test.

As shown in Table 7, VENT-II correctly predicted spillage depressurization, but did not correctly predict vent static pressure. VENT-II also predicted about 40 seconds of spillage when the CAZ pressure was -5.5 Pa when no spillage occurred during the experiment.

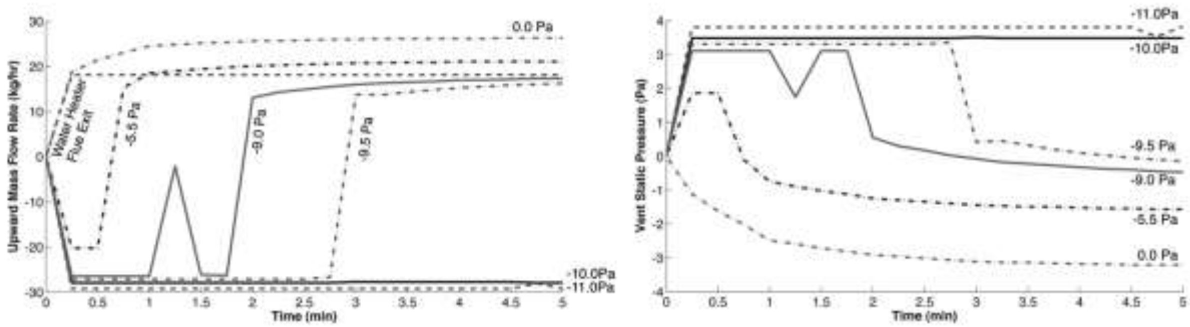
Table 7: Measured and simulated spillage states and vent static pressures for the orphaned water heater in Stockton, CA during summer conditions.

CAZ Pressure	State* (Spill / No Spill)		Vent Static Pressure Pa (in.w.c.)	
Pa (in.w.c.)	Measured	VENT-II	Measured	VENT-II**
0.0 (0.0)	No Spill	No Spill	-8.2 (-0.033)	-3.2 (-0.013)
-5.5 (-0.022)	No Spill	40 sec. Spill	N/A	-1.5 (-0.006)
-9.0 (-0.036)	Fluctuating Spill	Spill	N/A	-0.5 (-0.002)
-11.0 (-0.044)	Spill	Spill	N/A	3.7 (0.015)

* "Spill" indicates that the appliance spilled exhaust gases into the CAZ for the duration of the test (5 minutes). "Fluctuating Spill" indicates that the appliance fluctuated between spilling and not spilling for the duration of the test. "No Spill" indicates that the appliance did not spill at any time.

** Vent static pressure 5 minutes after appliance start-up.

When the CAZ pressure was -9.0 Pa, VENT-II predicted that the appliance will spill for the duration of the test, as shown in Figure 10, even though an upward draft was established after about 3 minutes. These results could be predicting some of the fluctuation between spilling and not spilling that occurred during our measurements. The 20 kg/hr (44 lbm/hr) increase and then decrease in simulated upward mass flow rate between 1 minute and 1.5 minutes for a CAZ pressure of -9.0 Pa will be addressed in Section 4.2. When the CAZ pressure was -9.5 Pa (-0.038 in.w.c.), VENT-II predicted that the water heater will spill for the duration of the test, but will backdraft for about 4.5 minutes (see Figure 10). Figure 10 also shows that VENT-II predicted a spillage depressurization of -10.0 Pa (-0.040 in.w.c.) if the appliance is to spill and backdraft continuously for 5 minutes, while the experimental results showed continuous spillage at -11.0 Pa for the duration of the test.



(A) Upward Mass Flow Rate **(B) Vent Static Pressure**

Figure 10: VENT-II predicted that the orphaned water heater located in Stockton, CA will spill (A) and backdraft (B) for the duration of the test (5 minutes) when the CAZ pressure, with respect to outdoors, is less than or equal to -10.0 Pa (-0.040 in.w.c.).

4.1.4 Spillage Depressurization for the Wall Furnace in Stockton, California

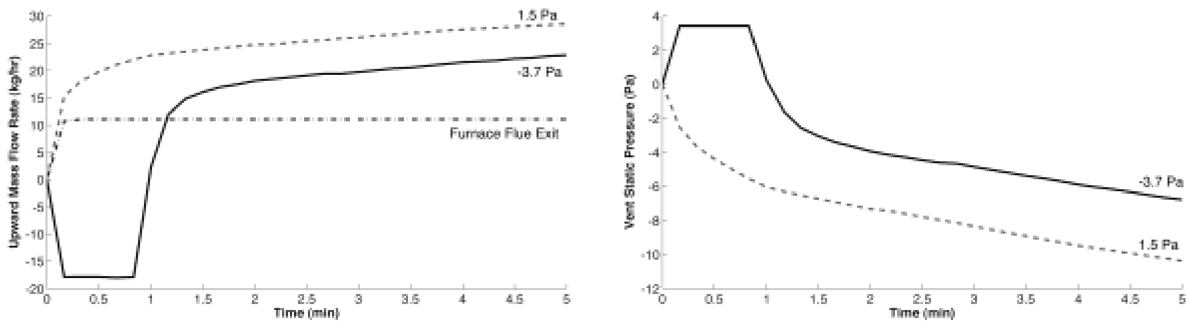
The wall furnace in Stockton, California also was tested for spillage during summer conditions. At the baseline CAZ pressure, 1.5 Pa (0.006 in.w.c.), the furnace drafted upward and did not spill. At -9.0 Pa (-0.036 in.w.c.), the furnace spilled for the duration of the test (5 minutes). As shown in Table 8, at the baseline CAZ pressure, VENT-II predicted no spillage, like the experimental results, and under predicted the vent static pressure as it did for the water heater. VENT-II could not predict vent static pressure or mass flow rate through the vent system for a CAZ depressurization greater than -3.7 Pa (-0.015 in.w.c.) because the solver continually failed. At a CAZ pressure of -3.7 Pa (-0.015 in.w.c.), as shown in Figure 11, VENT-II predicted that the furnace would spill and backdraft for about 1 minute before establishing an upward draft and no spillage. Problems with the solver are discussed further in Section 4.2.

Table 8: Measured and simulated spillage states and vent static pressures for the wall furnace in Stockton, CA during summer conditions.

CAZ Pressure Pa (in.w.c.)	State* (Spill / No Spill)		Vent Static Pressure Pa (in.w.c.)	
	Measured	VENT-II	Measured	VENT-II**
1.5 (0.006)	No Spill	No Spill	-16.4 (-0.066)	-14.4 (-0.058)
-9.0 (-0.036)	Spill	N/A	N/A	N/A

* "Spill" indicates that the appliance spilled exhaust gases into the CAZ for the duration of the test (5 minutes). "No Spill" indicates that the appliance did not spill at any time.

** Vent static pressure 5 minutes after appliance start-up.



(A) Upward Mass Flow Rate (B) Vent Static Pressure

Figure 11: VENT-II was unable to predict the upward mass flow rate (A), or vent static pressure (B) for the wall furnace located in Stockton, CA when the CAZ pressure, with respect to outdoors, is greater than -3.7 Pa (-0.015 in.w.c.). Although not shown here, VENT-II predicted no spillage or backdrafting for the baseline CAZ pressure, 1.5 Pa (0.006 in.w.c.).

4.2 Simulation Problems

We encountered two types of problems when using VENT-II to simulate vent systems. The first type was vent section location for single-appliance models. The second type was errors in the solver resulting in incomplete or erroneous solutions.

4.2.1 Vent Section Location for Single-Appliance Models

When creating a model for the orphaned water heater in Stockton, CA, we found that the predicted spillage depressurization was highly sensitive to vent configuration (i.e., a vent can be a part of the vent connector or a part of the common vent). The VENT-II manual does not clearly state the difference between the vent connector and the common vent for single-appliance vent systems. Therefore, we simulated the water heater using four different configurations (see Figure 12) with the same boundary conditions to explore how predicted spillage depressurizations change. For the first configuration (Figure 12A), the water heater vent system was designed such that the vent protruding through the roof was part of the common vent while the remainder of the vent system was part of the vent connector. In this case, VENT-II predicted a spillage depressurization of -10.0 Pa (-0.040 in.w.c.). If the vent configuration is changed to match Figure 12B, then the predicted spillage depressurization is -6.5 Pa (-0.026 in.w.c.). As vent sections are moved from the vent connector to the common vent, the predicted spillage depressurization decreases, as shown in Table 9.

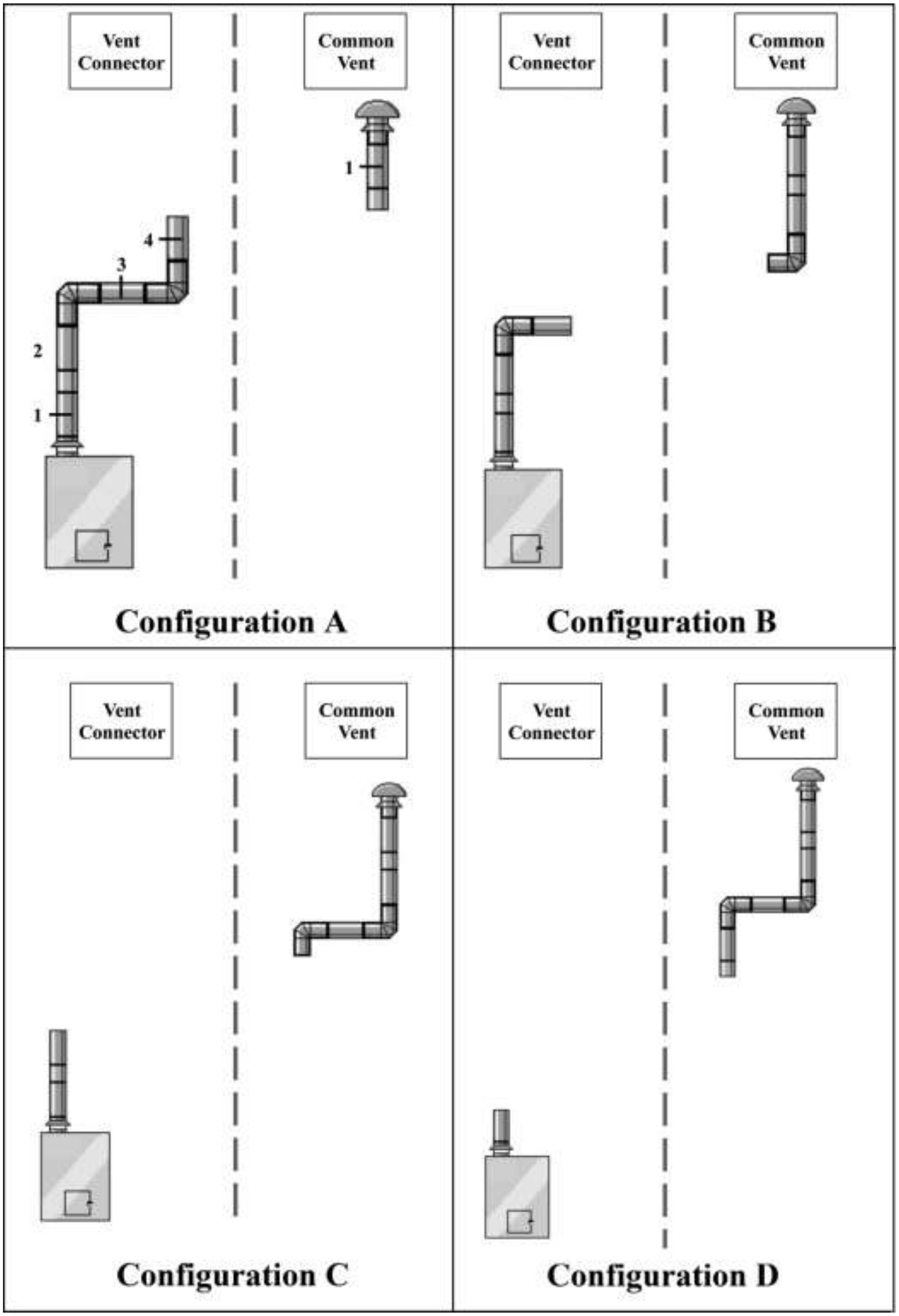


Figure 12: Changes in vent configuration for the model of the orphaned water heater in Stockton, CA.

Table 9: VENT-II results when changing vent configuration of the water heater.

Configuration	Number of Vent Connector Sections	Number of Common Vent Sections	CAZ Pressure Causing Spillage Pa (in.w.c.)
A	4	1	-10.0 (-0.040)
B	3	2	-6.5 (-0.026)
C	2	3	-5.8 (-0.023)
D	1	4	-2.0 (-0.008)

The vent configuration for the orphaned water heater in Berkeley, CA was also changed, but the predicted spillage depressurization remained constant. These results suggest that pressure, temperature, and mass flow rate calculations for the common vent use the outdoor temperature, while calculations for the vent connector use the indoor temperature. Following this definition would suggest that external vents (vents located outside the house) should be modeled in the common vent while internal vents should be modeled in the vent connector. The authors of VENT-II should verify this assumption and provide more detailed instructions for modeling single-appliance vent systems in VENT-II. When modeling the single-appliance vent systems in Section 4.1, we assumed that internal vents are part of the vent connector and external vents are part of the common vent.

4.2.2 Errors with the Solver

When running simulations in VENT-II, we frequently encountered inconsistencies with the solver. For several modeling conditions, VENT-II was either unable to converge to a solution or converged to an incorrect solution. When VENT-II was unable to converge to a solution, it would stop the solver and provide an error. For some models, the solver would complete part of the transient solution (stopping after two or three time steps) while in other models it would solve almost to the end of the defined appliance operating time before providing an error. When VENT-II converged to an incorrect solution, a sharp increase or decrease in the results for one time step was observed. For example, Figure 10 shows a sharp increase in mass flow rate at about 1.25 minutes when the CAZ pressure was set to -9.0 Pa (-0.036 in.w.c.). Other CAZ pressures, however, did not show this same phenomenon, thus indicating an error with the solver. One possible solution is to change the solver time step. VENT-II has a set time step of 5 seconds. In some cases, this time step may be too large to provide a convergent solution.

VENT-II also provided inconsistent errors when changing the depressurization for a model. For example, if the depressurization for the model of the orphaned water heater in Stockton, CA was set to -8.0 Pa (-0.032 in.w.c.), the solver did not provide solutions beyond the first minute of the operating cycle and displayed a solver error. However, when the depressurization was increased to -9.0 Pa (-0.036 in.w.c.), VENT-II was able to provide a solution for the entire operating cycle of the appliance without errors. These results suggest that solutions provided beyond -8.0 Pa

(-0.032 in.w.c.) might not be reliable even though the solver does not provide an error. From this study, we recommend that depressurizations leading to errors in the solver should be explored to increase the reliability of the solutions.

5. CONCLUSIONS

The purpose of this report was to determine whether VENT-II could be used to predict combustion appliance zone (CAZ) depressurizations leading to combustion spillage (spillage depressurization) by comparing simulated results from VENT-II with experimental data from four vent systems. From this study, we came to the following conclusions:

- VENT-II correctly predicted spillage depressurization for appliances operating in cold and mild outdoor conditions, but could not accurately predict spillage depressurization for hot outdoor conditions. This indicates that VENT-II is not reliable for predicting spillage depressurization over the entire year, especially where hot conditions occur.
- For a single-appliance vent system, moving vent sections from the common vent to the connector vent in VENT-II changes the predicted spillage depressurization.
- The algorithm used in VENT-II's solver needs further investigation. In many cases, the solver converged to an incorrect solution at a given time step, but would correct itself for the next time step, leading to inconsistent results.
- VENT-II provided inconsistent errors when changing CAZ depressurization for a model. In some cases, a specific CAZ depressurization would cause the solver to fail, but increasing or decreasing the CAZ depressurization slightly (±0.1 Pa, 0.0004 in.w.c.) would provide a complete solution.
- Due to inconsistent errors with the solver, an exact spillage depressurization could not be determined for a few cases. Therefore, VENT-II may not properly identify appliances that are spilling in practice.

Although VENT-II provides a first step towards modeling vent systems, further development is required to produce a reliable program that can correctly predict spillage caused by depressurization. From this study, we recommend that VENT-II's solver be investigated further and more detailed instructions be provided when modeling single-appliance vent systems.

6. REFERENCES

ASHRAE. 2012. "ASHRAE Handbook: HVAC Systems and Equipment". Atlanta, GA: ASHRAE.

BPI. 2012. "Building Performance Institute Technical Standards for the Building Analyst Professional, v1/4/12". Malta, NY: Building Performance Institute, Inc.

Detty, D.W., S.R. Mawalkar, and S.W. McKeown. 1998. "VENT-II User's Guide, Version 5.0". GRI Technical Report 98/0402. Chicago, IL:Gas Research Institute.

Glanville, P., L. Brand, and S. Scott. 2011. "Simulation and Experimental Investigation of Condensation in Residential Venting". ASHRAE Transactions, Vol. 117, Part 1. Atlanta, GA: ASHRAE.

Grimsrud, D.T. and D.E. Hadlich. 1999. “Initial Surveys on Depressurization-Induced Backdrafting and Spillage: Volume II - Twin Cities, MN”. GRI Technical Report 99/0187. Chicago, IL: Gas Research Institute.

Grimsrud, D.T. and D.E. Hadlich. 1995. “Residential Depressurization Protocol Development and Field Study”. GRI Technical Report 95/0324. Chicago, IL: Gas Research Institute.

Koontz, M.D., S. Natarajan, N.L. Nagda, and S.N. Nagda. 1999. “Initial Surveys on Depressurization-Induced Backdrafting and Spillage: Volume I - Washington, DC and Omaha, NE”. GRI Technical Report 99/0186. Chicago, IL: Gas Research Institute.

Koontz, M.D., S. Natarajan, N.L. Nagda, and Z. Li. 2001. “Follow-up Survey on Depressurization-Induced Backdrafting and Spillage in Omaha Residences”. GRI Technical Report 01/250. Chicago, IL: Gas Research Institute.

Nagda, N.L., Z. Li, M.D. Koontz, and S. Natarajan. 2002. “Depressurization-Induced Backdrafting and Spillage: Assessment of Test Methods”. ASHRAE Transactions, Vol. 108, Part 1. Atlanta, GA: ASHRAE.

NFPA. 2012. “National Fuel Gas Code, NFPA 54/ANSI Z223.1”. Quincy, MA: National Fire Protection Association.

PG&E. 2011. “Whole House Combustion Appliance Safety Test Procedure”. June. San Francisco, CA: Pacific Gas and Electric Company.

Rapp, V.H., B.C. Singer, J.C. Stratton, and C.P. Wray. 2012. “Assessment of Literature Related to Combustion Appliance Venting Systems”. Lawrence Berkeley National Laboratory Report, LBNL-5798E. Berkeley, CA.

Rutz, A.L., R.D. Fischer, and D.D. Paul. 1992. “Presentation of the VENT-II Solution Methodology”. GRI Technical Report 92/0149. Chicago, IL: Gas Research Institute.

Rutz, A.L. and N.P. Leslie. 1993. “Using VENT-II to Analyze Venting Installations”. ASHRAE Transactions, Vol. 99, Part 1. Atlanta, GA: ASHRAE.