NISTIR 6257

A Method of Test for Tracer Gas Test of an Outdoor Furnace Designed for Installation Without a Flue Pipe

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November 1998

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A METHOD OF TEST FOR TRACER GAS TEST OF AN OUTDOOR FURNACE DESIGNED FOR INSTALLATION WITHOUT A FLUE PIPE

ABSTRACT

An induced draft, gas-fired furnace originally designed for outdoor installation without a flue pipe was tested by the tracer gas method to determine its off-cycle power burner draft factor. When conducting the tracer gas test, the lack of the needed space for sensor installations and for shielding the sensors from ambient air disturbance creates an accuracy problem for the manufacturers and the testing agency to properly conduct the test. This report is to determine the feasibility of attaching a short flue pipe to the outdoor furnace during the optional tracer gas test to facilitate test measurement without significantly increasing the measured power burner draft factor due to the stack action of the added flue pipe. The results showed that it is possible to conduct the tracer gas test with a short flue pipe of less than 0.3 m (12 in.) without changing the calculated results for the value of Annual Fuel Utilization Efficiency (AFUE). Therefore, it is recommended that a short flue pipe, between 0.2 m to 0.3 m (8 in. to 12 in.) in length, be allowed in the Department of Energy (DOE) furnace test procedure during the optional tracer gas test for an outdoor furnace designed for installation without a flue pipe.

Key words: Annual Fuel Utilization Efficiency, ASHRAE Standard 103, DOE test procedure, flue gas measuring location, flue pipe, gas-fired furnace, induced draft furnace, outdoor installation, power burner draft factor, tracer gas test

ACKNOWLEDGEMENTS

This study was sponsored by the Office of Energy Efficiency and Renewable Energy, Office of Codes and Standards, U.S. Department of Energy. The authors would also like to express their appreciation to Mr. Charles Terlizzi, formerly engineering technician of the Building Environment Division, for the installation, instrumentation, development of data logging program and testing of the test furnace.

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1. INTRODUCTION

The procedure specified in the Department of Energy (DOE) test procedure for furnaces and the ANSI/ASHRAE Standard 103-1993 [1,2] for determining the off-cycle heat losses for furnaces with power burners introduces the application of a power burner draft factor, D_P. D_P is defined as the ratio of the flue gas mass flow rate through the furnace during the off-period to the flow rate during the on-period, where both flow rates are evaluated at the same steady-state on-period flue gas temperature [3,4]. In the test procedure, D_P is equal to either an assigned default value of 0.4 for power burner unit, or it can be determined experimentally by an optional tracer gas method. The tracer gas method is based on the assumptions that the off-cycle flue gas flow is buoyancy driven and the gas temperature decays exponentially after the burner is shut off. A one-time measurement of the flue gas temperature and the concentration of an injected tracer gas in a flue gas sample at a time approximately between 5 to 6 minutes after the burner is shut off can then be used to determine D_P.

When testing a furnace designed for indoor installation or as an isolated combustion system, the test procedure specifies that a five-foot vertical flue pipe shall be attached to the flue collar to simulate the field installation of the furnace in an enclosed space. The length of the flue pipe generally provides added draft to the off-cycle flue gas flow. However, for an induced draft furnace designed to be located outdoors, there is no need to exhaust the flue gas to the outside via a chimney. Therefore, for an outdoor furnace, manufacturer may specify that no flue pipe is to be attached to the flue collar during normal installation in the field. The advantage of no flue pipe is that without the added draft created by a flue pipe, the off-cycle flue gas flow and flue loss will be reduced with a corresponding increase in the heating seasonal efficiency, or the Annual Fuel Utilization Efficiency (AFUE) of the furnace. However, without the flue pipe, problem may arise with respect to data accuracy during the energy efficiency testing of the furnace.

In the furnace test procedure, the measurements of flue gas temperature and the collection of the flue gas sample (for measurement of CO_2 and tracer gas concentration values) are usually taken inside the attached flue pipe in a plane within 0.31 m (12 in) downstream of the flue collar connection. This arrangement assures that the measurement plane is at a distance away from the effect of any ambient air movement at the flue pipe outlet. This arrangement also provides better mixing of the flue gas for the temperature and tracer gas concentration measurement. Without the flue pipe, the space for the installation of the temperature sensors and sample collection tubes becomes very limited and data would have to be taken either inside the flue collector box, or at a plane close to the exit flue collar. The latter location is much simpler to install the instruments since no drilling of sampling holes either through the collector box or into the flue passage at the exit from the combustion blower is required (as easy access to these locations is usually not possible). However, any air disturbance near the flue collar during the off-cycle will cause possible inaccuracy in the measured data near the flue collar exit location. Careful isolation of the flue outlet from any air disturbance in the test area near the furnace would be required in order to minimize this air disturbance effect. This would require additional effort in the test setup, and may still not achieve the desired result.

One method to avoid this ambient air disturbance problem is to attach a short length of flue pipe to the flue collar for the installation of the temperature sensors and flue gas sampling tube. This added flue pipe generally would increase the off-cycle draft and flue loss and resulting in a lower AFUE. However, in the test procedure, there is a provision that if the measured D_P is less than or equal to 0.10, a default average minimum value of 0.05 shall be assigned for the calculation of the off-cycle flue loss. The reason for prescribing this average default value in the test procedure is to avoid the difficulty (due to the very low flow rate of the flue gas during the off-cycle) of repeatedly sampling the tracer gas concentration level to obtain a repeatable concentration value. Therefore, it was envisioned that if the added flue pipe is short enough, the increased draft might not cause the measured D_P to go over the specified limit of 0.10. The value of AFUE will then be calculated on the basis of the default D_P value of 0.05 and will not change from the one tested under the "no flue pipe" configuration.

The purpose of this project was to study quantitatively the effect of the flue pipe length on the off-cycle losses, and to develop a revised tracer gas test procedure for power burner furnaces designed for outdoor installation. A commercially available outdoor gas-fired furnace with an induced draft combustion blower and designed for installation without a flue pipe was obtained and tested at the National Institute of Standards and Technology (NIST) for the off-cycle draft factor using the tracer gas method. The furnace was first tested as designed, and then tested with several different lengths of vertical upward flow flue pipe attached to the flue collar. The results showed that it is feasible to employ a short length of flue pipe to facilitate the tracer gas test without affecting the resulting flue loss and AFUE values. The various test results and comparisons, and the recommended length of flue pipe to be used for an outdoor furnace are presented in this report.

2. TEST SET-UP

The test furnace is a gas-fired, induced draft furnace designed for outdoor installation. In place of a flue pipe, the furnace employs a triangular-shaped rain-hood attached to the horizontal, rectangular flue collar on the furnace jacket and oriented downward to discharge the flue gas as illustrated in Figure 1. In addition, the furnace has a special design feature where the flue outlet is located lower than the combustion blower housing. The manufacturer claimed that this special feature would further restrict the airflow through the heat exchanger during the off-cycle. In the meantime, the manufacturer claimed that the reduced airflow caused the measurement of the off-cycle draft factor difficult to conduct by the method specified in the existing test procedure. The furnace heat exchanger consists of serpentine-shaped steel tubes manifold together at the flue collector box. The flue collection box is connected to the induced draft combustion blower that discharges the flue gas through the flue collar. The furnace has a nameplate input rating of 36.63 kW (125,000 Btu/h).

The test furnace was installed on a 0.13 m (5 in) high platform in a temperature controlled, high-bay test facility. The rain-hood covered horizontal combustion air inlet is located 0.43 m (17 in) above the ground and 0.2 m (8 in) directly below the rain-hood covered flue gas outlet of the furnace (Fig. 1). To assure that the products of combustion are exhausted to the outdoors, and to reduce air disturbance, a 1 m by 1 m (39.4 in by 39.4 in) square apron enclosure 1.22 m (48 in) high (starting from the floor up), was built around the flue gas outlet. Two vertical openings in the apron wall, 0.25 m by 0.91 m (10 in by 36 in), were cut out for free air circulation. The opening on the top wall of the apron enclosure was fitted to a funnel shaped exhaust hood 0.61 m (24 in) above the flue gas outlet opening. The top of the funneled exhaust hood was connected to a 0.18 m (7 in) diameter vertical power-vented sheet metal chimney, which was vented through the building roof to the outside. During the tests, the power to the chimney exhaust fan was turned off during the burner off cycle when the tracer gas tests were conducted. Tracer gas test runs were conducted for a number of different length flue pipes as well as with the furnace in its designed (rain-hood flue outlet) configuration. For the tests with the added flue pipes, the flue rain-hood was taken off. All the test flue pipes have the same rectangular cross-sectional area as the horizontal flue outlet collar. Figures 2 shows a schematic of the test furnace with an attached test flue stack. Figure 3 shows a schematic of a 0.2 m (8 in) test flue pipe provided by the furnace manufacturer for the tests. Various lengths of extensions were added to this flue pipe for tests with different flue pipe lengths. Figure 4 shows a schematic of the test furnace with the apron enclosure and the test flue pipe. During the tests, flue gas temperature and tracer gas concentration data were recorded every 5 seconds and observed on the desktop computer screen during the off-cycle.

The test furnace was instrumented as specified in the ANSI/ASHRAE 103-1993 [2]. For the tracer gas tests, sampling and injection metal tubes 9.5 mm (3/8 in) diameter were installed. For the test with the flue rain-hood at the flue outlet, three equal length and equally spaced sampling tubes were inserted (by drilling holes through the wall) into the flue collector box upstream of the combustion blower and manifold together. Flue gas temperature sensors were inserted to the same locations as the sampling tubes and at the exit of the combustion blower. This arrangement is necessary after preliminary tests showed that sampling at the flue exit rain-hood location gave unstable readings of the flue gas temperature and tracer gas concentration even with the apron wall enclosure. For tests with the test flue pipes, another sampling tube and temperature sensors were inserted in the test flue pipe at a plane (cross-section) .1 m (4 in) downstream of the furnace flue collar opening. Tracer gas injection tubes were inserted into the entrance to each of the tubular serpentine heat exchangers to reduce the possibility that part of the injected tracer gas might be backing out of the combustion air inlet. In addition, one tube was inserted through a drilled hole at the exit from the combustion blower to return the sampled gas back to the flue gas stream. The flue gas samples were analyzed for the carbon dioxide (CO_2) and carbon monoxide (CO) concentrations by non-dispersive infrared gas analyzers. The CO_2 analyzer was calibrated with reference gas with certified CO_2 concentrations of 2.92%, 5.20%, and 9.99%. The CO analyzer was calibrated with reference gas (mixture of nitrogen and carbon monoxide) with certified CO concentrations of 10.5 μL/L, 79.37 μL/L, and 394.8 μL/L (ppm). During the test, the sample gas was passed through a beaker immersed in an ice-water mixture and a desiccant dryer to obtain the dry sample gas as specified in the ANSI/ASHRAE Standard 103.

The temperature sensors and the output signals from the infrared gas analyzers and the gas meter counter were connected to a data acquisition system and a desktop computer. The computer controlled the data scan rate by the use of off-the-shelf data acquisition and control application software. Data recording interval was 5 seconds. Data were analyzed using a commercially available spreadsheet program.

3. TEST CONFIGURATIONS AND PROCEDURE

Two test configurations were tested for this study. One was the original configuration with the flue rain-hood attached to the flue outlet collar and the other was with various lengths of flue pipe attached to the flue outlet collar (in place of the flue rain-hood). The length of flue pipes were 0.20 m, 0.31 m, 0.46 m, and 0.61 m (8, 12, 18, and 24 inches). Mixture of carbon monoxide and nitrogen with a certified carbon monoxide concentration was used as the tracer gas. Three flue gas sampling tubes installed in the flue collector box through equally spaced holes drilled in the frontal flue collector box walls and manifold together were used for the flue gas CO_2 and the tracer gas (CO) measurements for the test with the original configuration. One flue gas sampling tube 0.1 m (4 in) from the bottom of the vertical flue pipe was used for the gas concentration measurement for tests with the test flue pipes. The flue gas temperature from the exit of the combustion blower was used for the calculation of the furnace steady-state efficiency and the off-cycle flue gas flow rate for all of the tests. It was assumed that the mixing action of the combustion blower would give a better indication of the flue gas temperature than the average value from the three sensors in the flue collector box. Values of the power burner draft factor D_P by the trace gas method, the off-cycle flue losses and the Annual Fuel Utilization Efficiency (AFUE) for each of the flue pipe lengths were calculated using the computerized ASHRAE Standard 103 computer program "AFUEBF".

The tracer gas test procedure is as follows:

(1) Run the furnace to steady-state conditions (45 minutes from burner-on). Record the average gas temperature, and carbon dioxide (CO_2) concentrations.

(2) Start the 45-minute cool-down test by turning the burner off. Start the injection of the tracer gas (carbon monoxide) at two minutes before the burner is shut off at a constant injection flow rate of 0.0157 L/s (0.0333 cfm) (approximately 0.07% of the on-cycle flue gas flow rate of 22.4 L/s (47.4 cfm) and 2.3% of the off-cycle air flow rate through the heat exchanger). The injected tracer gas has a certified concentration of 10,000 μL/L (ppm). The injection is through injection tubes extended approximately 0.61 m (24 in) into the flue gas entrance of each of the steel serpentine heat exchanger tubes. At the same time, start sampling the tracer gas at a sampling flow rate of 0.0197 L/s (0.0417 cfm). Continue the tracer gas injection and sampling for the next 20 minutes, then stop the tracer gas injection and sampling. Continue the cool-down for the remaining 25 minutes test period. Then turn on the burner to start a 5-minute heat-up test for the measurement of flue gas temperature. Stop the test after the 5-minute heat-up period.

4. TEST RESULTS AND DISCUSSION

The results of the tracer gas tests are shown and discussed below. As specified in ASHRAE Standard 103, flue gas temperature and tracer gas concentration data measured at 5.5 minutes after the burner was turned off were used to compute the power burner draft factor, the off-cycle draft loss, and the AFUE value. The ASHRAE computer program AFUEBF that follows the calculation procedure of ASHRAE Standard 103 was used to calculate these values as well as the value of the furnace's steady-state efficiency ($EFFY_{SS}$). Also, a spreadsheet program was used for data reduction.

Figure 5 shows the data of the flue tracer gas concentration (measured in the flue collector box for the flue rain-hood configuration, and in the flue pipe for the test flue pipe cases) one minute after the termination (burner shut-off) of the 45 minutes steady-state operation. The five curves are the results for the flue rain-hood, and the 0.20 m, 0.31 m, 0.46 m, and 0.61 m (8 in, 12 in, 18 in, and 24 in) length flue pipes, respectively. It is noted that because of the length of the connecting tube from the sampling tube opening to the infrared analyzer, there is approximately a 30 seconds transport time delay from the sampling point to the analyzer. Also, the test furnace has a fixed post purge period of 20 seconds where the combustion blower continues to run after the burner off. It is seen from Figure 5 that the flue tracer gas concentration rose rapidly in the first two minutes (taking into account the transport time delay) after the burner was off, indicating a rapid decrease of the air flow through the heat exchanger. The concentration level continued to increase 15 minutes after the burner off. As expected, the tracer gas concentration level decreases (at any particular time) with increasing flue pipe length, showing the effect of the stack action of the added flue pipe on off period air flow rate.

Figure 6 shows the air flow rate through the heat exchanger at the corresponding flue tracer gas concentration levels between one and 15 minutes after the burner shut off. Figure 7 shows the flue gas temperature decay during the off-cycle. The plot of the temperature data begins at one minute before the termination (burner shut-off) of the 45 minutes steady state operation to show the steady state flue gas temperature. It is seen that contrast to the larger variation of the tracer gas concentration data with respect to the flue pipe length, the off-cycle flue gas temperature varied only slightly among tests with different flue pipe lengths including the rain-hood configuration. The higher steady state flue gas temperature for the test with the flue rain-hood (confirmed by repeated tests) is probably caused by the lower flue draft when compared with the tests with the added test flue pipe.

Figure 8 shows the measurement of the flue gas temperature at two locations during the test with the rain-hood attached. One location was at the exit of the combustion blower and the other location was at the flue collar where the rain-hood was attached. It is seen that the latter location gave a much lower temperature reading, indicating the inaccuracy of taking flue gas data too close to the ambient environment. Figure 9 shows the measurement of the flue gas temperature at two locations during the test with a test flue pipe attached. In this case the temperature inside the flue pipe downstream of the flue collar location was very close to the temperature at the combustion blower exit as indicated by the agreement during the steady state operation (between time 44 min and 45 min on Figure 9). The difference between the two temperature readings during the off-cycle is likely due to the poorer mixing of the flue gas stream with the combustion blower off. Figure 10 shows the measurement of the tracer gas in the flue gas at two sampling locations in two tests conducted with the 12-inch test flue pipe. One test was with the sampling location inside the flue collector box (which was the sampling location used for the tests with the flue rain-hood) and the other test was with the sampling location inside the test flue pipe. It is seen that the tracer gas concentrations at the two sampling locations measured during the two tests were in good agreement. Therefore, if test is conducted with an attached test flue pipe, tracer gas measurements may be made in the flue pipe instead of the flue collector box. This avoids the need for drilling holes through the flue collector box and simplifies the optional tracer gas test process.

Table 1 shows the calculated D_P and AFUE values for the different flue pipe lengths on the basis of the measured tracer gas concentration data, including the as-designed configuration with the flue rain-hood. The steady state flue gas CO_2 concentration value and the flue gas temperature data for the steady state, cool-down, and heat-up tests were from the test run with the flue rain-hood. The tracer gas concentration data were from the tracer gas test runs with the test flue pipe attached. This was the test procedure requested by the furnace manufacturer in its "Petition for Waiver" to the Department of Energy (i.e., using the CO_2 and temperature data from test without the test flue pipe, and using the tracer gas data from the optional tracer gas test with the added test flue pipe).

Table 1. Variation of the draft factor (D_P) and AFUE with respect to flue pipe length

Flue Pipe Length m (in)	D_P (Measured) -	$EFFY_{SS}$* %	AFUE (With measured D_P) %	AFUE (With default D_P=0.05) %
0 (0)**	0.063	81.19	78.81	79.03
0.20 (8)	0.072	81.19	78.68	79.03
0.31 (12)	0.078	81.19	78.57	79.03
0.46 (18)	0.106	81.19	78.12	Not Applicable
0.61 (24)	0.113	81.19	78.01	Not Applicable

* $EFFY_{SS}$ for all cases is based on temperature and CO_2 data from rain-hood only test.
** Rain-hood only. (No flue pipe attached).

From the above results, it is seen that D_P would increase with an attached flue pipe, and its value increases with increasing flue pipe length. However, for a test flue pipe length of 0.3 m (12 in) or less, the measured D_P is less than 0.10. Therefore, as specified in the test procedure, a default value of 0.05 for D_P is assumed in the calculation for the AFUE value when the furnace is tested by the tracer gas method with an attached flue pipe of 0.3 m (12 in) or less. The last column in Table 1 shows the results of AFUE when D_P was set to equal to the default value of 0.05 as allowed in the test procedure. As shown in Table 1, there would be a slight decrease in the value of AFUE of approximately 0.25 percentage points with a 0.3 m (12 in) flue pipe if the measured D_P were used in the calculation. However, there was no change in the AFUE between the no flue pipe (rain-hood) case and the 0.3 m (12 in) flue pipe case when the default value of 0.05 for D_P was used. This indicates that to facilitate the conducting of the tracer gas test, a short flue pipe, from 0.2 m to 0.3 m (8 in to 12 in) in length, can be attached to this furnace to perform the tracer gas test without any change in the calculated value for AFUE.

5. CONCLUSIONS

An induced draft, gas-fired furnace originally designed for outdoor installation without a flue pipe was tested by the tracer gas method to determine its off-cycle power burner draft factor. Usually, when conducting the tracer gas test, the flue pipe provides a convenient location for the installation of the flue gas temperature sensors and the tracer gas sampling tube. The location not only provides the needed space for the sensors, it also shields the sensors from ambient air disturbance that may affect the accuracy of the measured data. For an outdoor furnace designed to operate without a flue pipe, the lack of the needed space for the sensors and shielding creates an accuracy problem for the manufacturers and the testing agency to properly conduct the tracer gas test. This report is to determine the feasibility of attaching a short flue pipe to the furnace during the optional tracer gas test in facilitating test measurement without significantly increasing the measured power burner draft factor due to the stack action of the added flue pipe during the burner off period. A furnace designed to operate with only a rain-hood was first tested as designed and then tested with four short vertical flue pipe of different lengths to determine the effect of an added flue pipe as well as its length on the measured draft factor. The results showed that it is possible to conduct the tracer gas test with a short attached flue pipe of less than 0.3 m (12 in) to facilitate the test without changing the calculated results for the value of AFUE. As expected, the results showed that the draft factor would increase with an attached flue pipe, however, the increment was small for a short flue pipe.

Based on the above results, it is recommended that the DOE furnace test procedure be modified to allow for the attachment of a short vertical flue pipe, 0.2 m to 0.3 m (8 in to 12 in) in length, during the optional tracer gas test for an outdoor furnace designed for installation without a flue pipe.

REFERENCE

1. Federal Register, DOE 10 CFR Part 430, Appendix N to Subpart B of Part 430, "Uniform Test Method for Measuring the Energy Consumption of Furnaces," May 12, 1997.

2. ANSI/ASHRAE Standard 103-1993, "Methods of Testing for Annual Fuel Utilization Efficiency of Residential Central Furnaces and Boilers," ASHRAE, Atlanta, GA 1993

3. Kelly, G.E., Chi, J., Kuklewicz, M.E., "Recommended Testing and Calculation Procedures for Determining the Seasonal Performance of Residential Central Furnaces and Boilers," NBSIR 78-1543, March 1978.

4. Park, C., Mulroy, W.J., Kelly, G.E., "A Study of the Dynamic Flue-Gas Temperature and Off-period Mass Flow Rate of a Residential Gas-Fired Furnace," NBS Technical Note 999, July 1979.

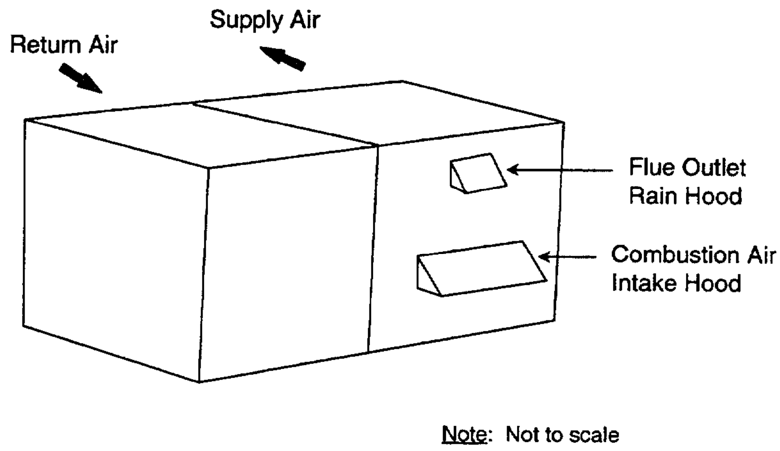

Figure 1. Schematic of outdoor furnace

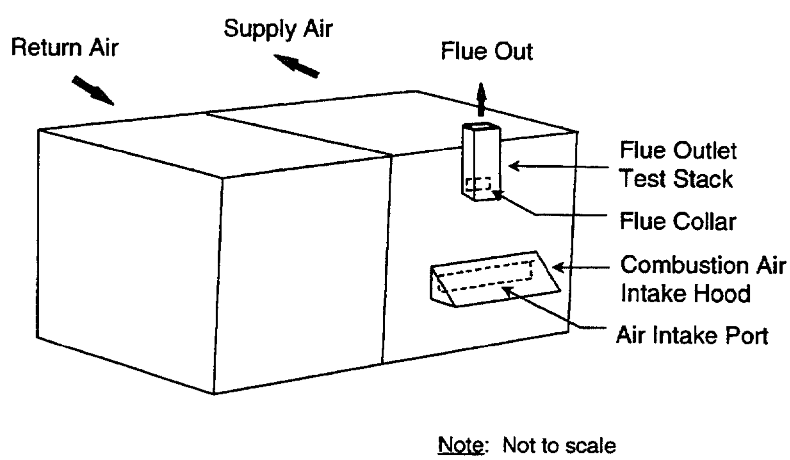

Figure 2. Schematic of outdoor furnace with test stack

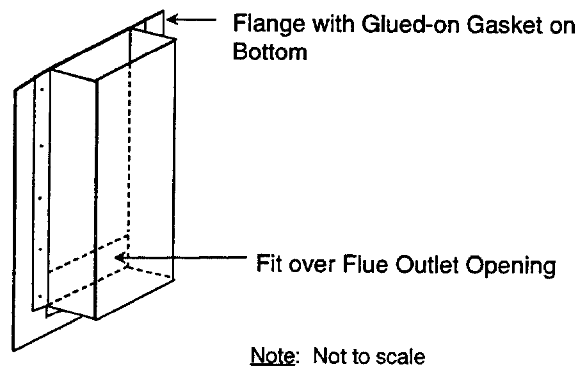

Figure 3. Schematic of the test stack

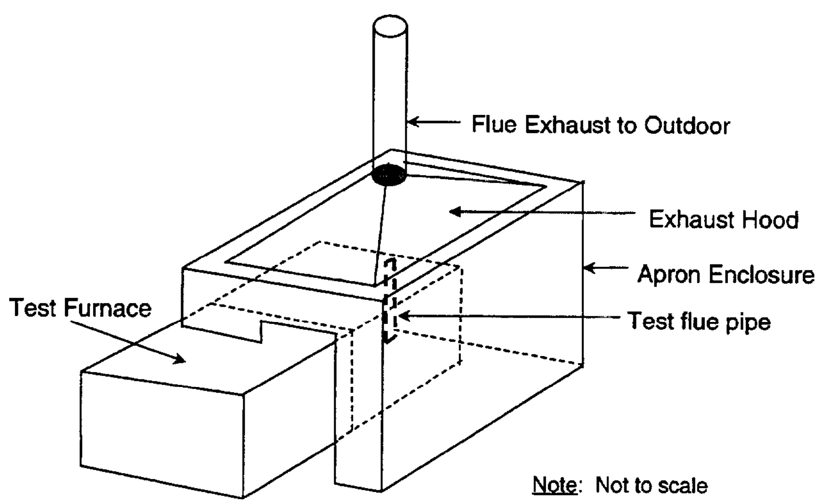

Figure 4. Schematic of apron enclosure around the furnace

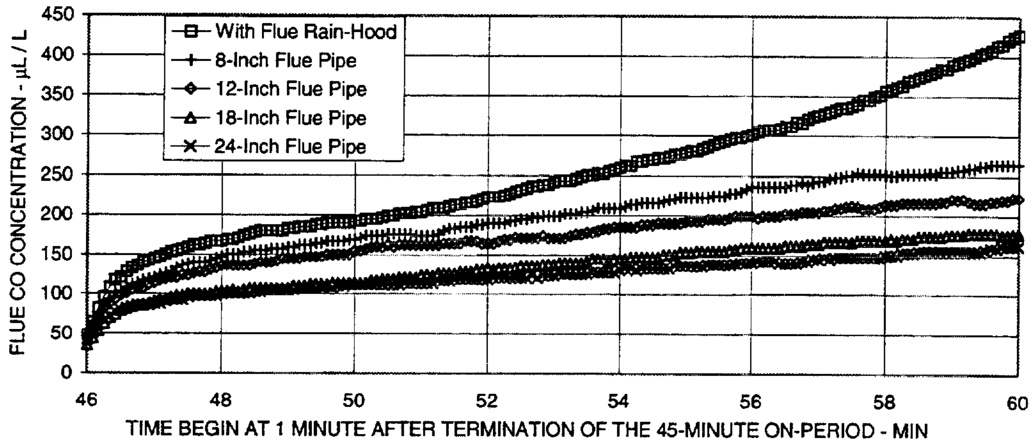

Figure 5. Off-cycle tracer gas concentration in flue gas with different length test flue stack

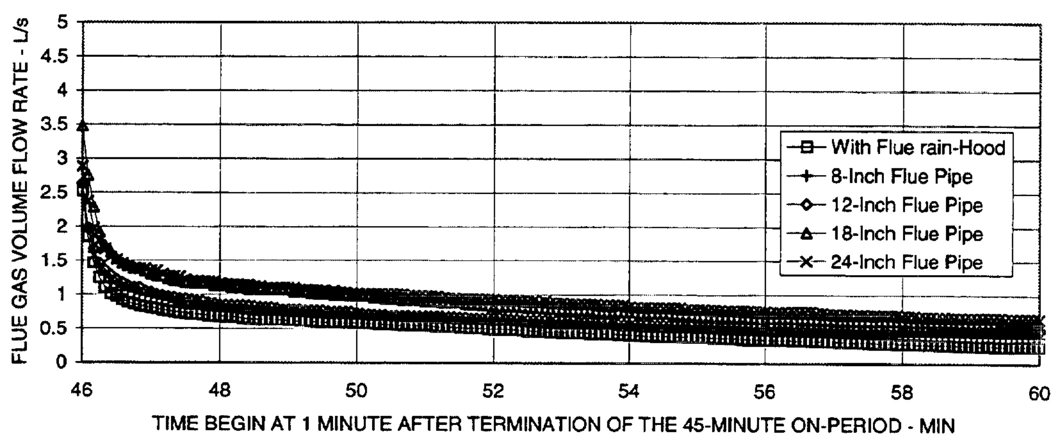

Figure 6. Off-cycle flue gas volume flow rate with different length test flue stack

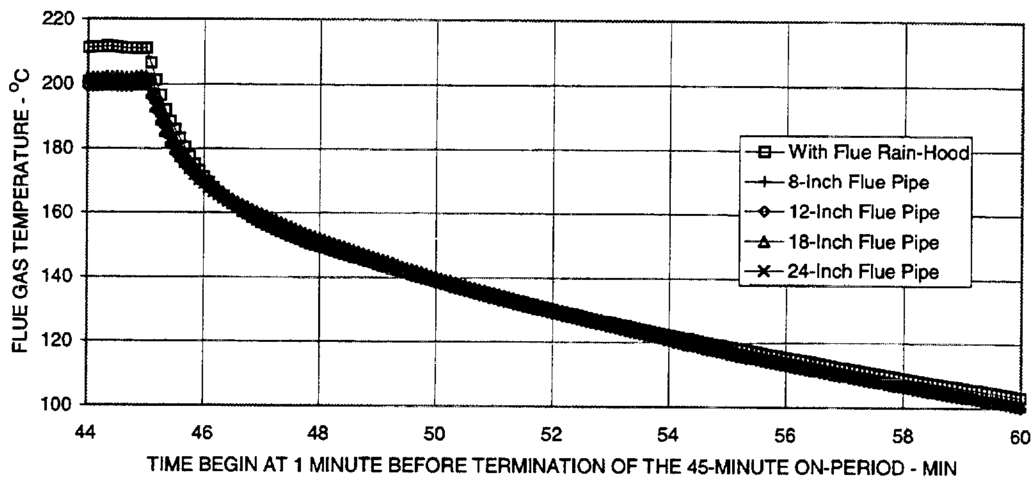

Figure 7. Off-cycle flue temperature at combustion blower exit with different length test stack

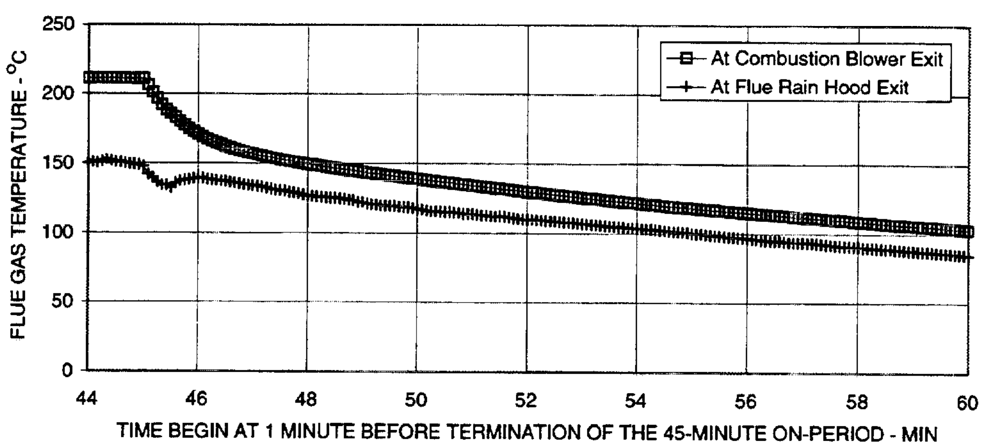

Figure 8. Comparison of off-cycle flue gas temperature at two measuring locations (test configuration – with flue rain-hood)

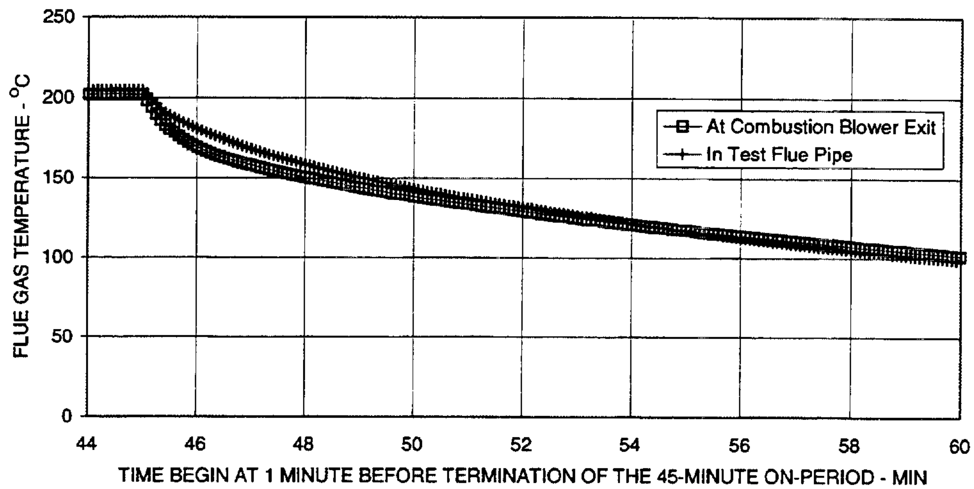

Figure 9. Comparison of off-cycle flue temperature at two measuring locations (8-inch test flue stack)

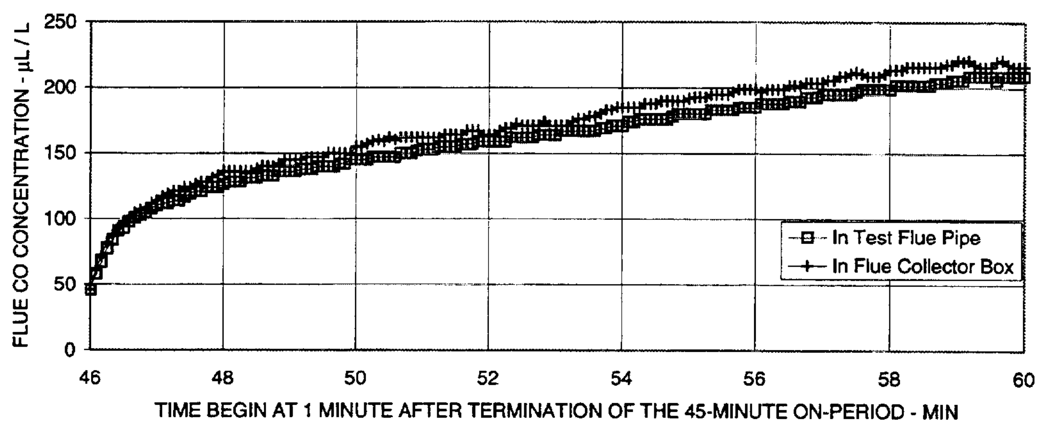

Figure 10. Comparison of tracer gas concentration at two sampling locations (12-inch test flue stack)

APPENDIX - Measurement Uncertainty

The calculation of the off-cycle flue gas mass flow rate at time t is given in ASHRAE Standard 103-1993 [2] as:

$$M_F = \frac{(C_{Tm} - C_T)V_T \rho_F}{C_T}$$

where C_{Tm} is the injected tracer gas with a certified CO concentration level, C_T is the tracer gas concentration in the flue gas sample, V_T is the volume flow rate of the injected tracer gas, and ρ_F is the density of the injected tracer gas.

Based on a propagation of uncertainty analysis, the combined standard uncertainty, u_{Mc}, of the measured M_F, normalized (with M_F) to a percentage basis, can be expressed as:

$$u_{Mc} = \sqrt{\left(\frac{\partial M_F}{\partial C_{Tm}}\frac{\Delta C_{Tm}}{M_F}\right)^2 + \left(\frac{\partial M_F}{\partial C_T}\frac{\Delta C_T}{M_F}\right)^2 + \left(\frac{\partial M_F}{\partial V_T}\frac{\Delta V_T}{M_F}\right)^2 + \left(\frac{\partial M_F}{\partial \rho_F}\frac{\Delta \rho_F}{M_F}\right)^2}$$

where

$$\frac{\partial M_F}{\partial C_{Tm}} = \frac{\rho_F V_T}{C_T}$$

$$\frac{\partial M_F}{\partial C_T} = -\frac{\rho_F V_T C_{Tm}}{C_T^2}$$

$$\frac{\partial M_F}{\partial V_T} = \frac{\rho_F (C_{Tm} - C_T)}{C_T}$$

$$\frac{\partial M_F}{\partial \rho_F} = \frac{V_T (C_{Tm} - C_T)}{C_T}$$

Substituting the expressions for M_F and the partial derivatives into the equation for u_{Mc}, gives,

$$u_{Mc} = \sqrt{\left(\frac{C_{Tm}}{C_{Tm} - C_T}\frac{\Delta C_{Tm}}{C_{Tm}}\right)^2 + \left(-\frac{C_{Tm}}{C_{Tm} - C_T}\frac{\Delta C_T}{C_T}\right)^2 + \left(\frac{\Delta V_T}{V_T}\right)^2 + \left(\frac{\Delta \rho_F}{\rho_F}\right)^2}$$

The certified accuracy of the concentration of CO in the injected tracer gas, C_{Tm} (at 10,000 μL/L), is ±1%. The flow meter for the measurement of the volume flow rate of the injected tracer gas, V_T, has a resolution of ±1%. The infrared analyzer has a sensitivity of ±1% at full scale (±10 μL/L at

1000 μL/L), or approximately ±6.5% at the level of concentration of 110 μL/L to 200 μL/L (of the measured C_T at the required measurement time of 5.5 minutes after the burner was shut off) in the flue gas sample. The density of the injected tracer gas is a function of the temperature and pressure entering the flow meter and has an estimated error of 0.4%. Based on these individual measurement uncertainties, and with C_{Tm} = 10,000 μL/L and C_T = 162 μL/L as an example of the measured value (for the 12-inch test flue stack), the combined standard uncertainty of the calculated off-cycle flue gas mass flow rate was approximately u_{Mc} = 6.6%.

From the above estimation, it is seen that the major uncertainty on the measurement of the off-cycle flue gas flow was the sensitivity of the infrared analyzer in the measurement of the tracer gas concentration in the flue gas sample. The determination of the power burner off-cycle draft factor D_P involves a complex calculation procedure based on the steady state flue gas temperature and the flue gas temperature and tracer gas concentration level at the required measurement time (of 5 to 6 minutes after the burner was shut off), and other theoretical assumptions on the fluid dynamics and temperature profile of the off cycle flue gas flow [4]. The calculation for D_P was part of the computer program AFUEBF developed by ASHRAE for the calculation of the furnace annual fuel utilization efficiency AFUE. Using test data from the 12-inch test flue stack as an example with the maximum possible variation of the measured tracer gas concentration of 162 μL/L ±10 μL/L and the computer program AFUEBF, the value of D_P was found to be within 0.078 ±0.005 for the case of the 12-inch test stack. Therefore, the uncertainty for the measurement of D_P in this investigation is estimated to be that of the uncertainty u_{Mc}, 6.6%.