NISTIR 4908

Evaluating the Off-Cycle Losses of a Gas-Fired, Power Vented Furnace Employing Post Purge

Stanely T. Liu
George E. Kelly
Charles P. Terlizzi

Building and Fire Research Laboratory
Gaithersburg, Maryland 20899

NIST

United States Department of Commerce
Technology Administration
National Institute of Standards and Technology

NISTIR 4908

Evaluating the Off-Cycle of a Gas-Fired, Power Vented Furnace Employing Post Purge Control Systems

Stanley T. Liu
George E. Kelly
Charles P. Terlizzi

August 1992

U.S. Department of Commerce
Barbara Hackman Franklin, *Secretary*
Robert M. White, *Under Secretary for Technology*
National Institute of Standards and Technology
John W. Lyons, *Director*

Prepared for:
U.S. Department of Energy
Office of Conservation &
Renewable Energy
1000 Independence Ave., SW
Washington, DC 20585

ACKNOWLEDGMENT

The authors of this report would like to acknowledge the U.S. Department of Energy for funding this project.

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

The procedure specified in the Department of Energy (DoE) test procedures for furnaces [1] and the ANSI/ASHRAE Standard 103-1988 [2] for determining the off-cycle heat losses for furnaces with power burners involves the use of a power burner draft factor, D_P. D_P is equal to either an assigned default value of 0.4, or a value determined 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, therefore a single measurement of the flue gas temperature and the concentration of a tracer gas at a time between 5 to 6 minutes after the burner is shut off can be used to determine D_P. This procedure works well if the burner blower stops either immediately or after a short post purge period (less than 5 seconds, for example) after the burner is shut off. Post purge is the continued operation of the burner blower for a period of time after the main burner is shut off. For post purge times longer than a few seconds, the existing test procedure [1,2] will produce errors in the annual fuel utilization efficiency (AFUE) since with the burner blower running during post purge, the mass flow rate through the heat exchanger is equal to or even greater than when the burner is on. This flow cools down the heat exchanger much more rapidly than if there is no post purge (where the flow is by natural convection only). Therefore, a large portion of the off-cycle losses will occur during the post purge period. There is usually a distinct change in the pattern of the flue gas temperature between the post purge period and the period after post purge. After the post purge period, the off-cycle temperature (and mass flow rate) will be reduced to a much lower value than if there is no post purge. The existing one point optional tracer gas measurement, performed during the period after the post purge (at 5 to 6 minutes after the burner-off), will therefore give an incorrect D_P value (and a low off-cycle loss). The longer the post purge is, the greater the error will be. The optional tracer gas procedure in the current furnace/boiler test procedure will therefore give too high an AFUE value for power vented burners using long post purge time.

The purpose of this project was to study quantitatively the effect of the length of post purge time on the off-cycle losses, and to develop a revised tracer gas test procedure for power burners employing post purge. A commercially available gas furnace with an induced combustion blower for power venting and with provisions for employing post purge was tested at the National Institute of Standards and Technology (NIST). Tracer gas test runs were conducted for a number of different post purge periods after the burner shuts off. Flue gas temperature and tracer gas concentration data were recorded every 5 seconds and examined during both the purging period and the period following purging. Off-cycle sensible heat losses were computed for both periods using the 5-second data. Comparisons were made with the results obtained by the existing optional trace gas procedure where data from one point were used to compute a flue draft factor D_F for the calculation of the off-cycle loss for the entire off-cycle interval. Large errors in the results obtained by using the existing optional procedure were found. A proposed method was developed which involves a new procedure to compute the off-cycle losses during the purging period and a modified ANSI/ASHRAE 103-1988 procedure to compute the off-cycle losses for the period following purging. The various test results and comparisons, and the development of the proposed calculation procedures are presented in this report.

2. OBJECTIVES

The objectives of the study were:

1. Determine the off-cycle loss of a power burner furnace with different post purge time periods using detailed tracer gas measurements over the entire off-cycle period.

2. Check the feasibility of conducting tracer gas measurement in the stack on power vented burners equipped with a small vent spillage passage (one with a draft relief air opening that is less than 10% of the total stack cross-sectional area) that is not sealed during the test.

3. Develop a revised calculation procedure and a revised optional tracer gas test procedure similar to the existing optional tracer gas procedure to be incorporated into the ANSI/ASHRAE 103-1988 and the next update of the DoE furnace test procedure for the calculation of the AFUE value for a power vented burner employing post purge.

3. TEST SET-UP AND INSTRUMENTATION

The test furnace (Figure 1) is a gas-fired, power vented furnace with an induced draft combustion blower. The furnace was installed in a high-bay laboratory space with controlled space temperature. An electronically controlled ignition device is used to automatically light the burner. The furnace has a name plate input rating of 26.38 kW (90000 Btu/hr). The heat exchanger consists of four serpentine-shaped tubes manifold together at the exit. The exit manifold enters a lightly insulated (approximately 12 mm (0.5 in.) of glass fiber batt insulation) flue collection box which in turn is connected to a squirrel-cage type combustion blower (draft inducer). The induced draft combustion blower exits to a 76 mm (3 in.) diameter flue collar. A vent spillage (draft safeguard) passage with a net opening area of 9.8% of the net flue collar cross-sectional area is located between the combustion blower exit and the flue collar. A 1.52 m (5 ft) length of insulated test stack (R = 1.233 $s{\cdot}m^2{\cdot}K/J$ (7 $hr{\cdot}Ft^2{\cdot}{}^{\circ}F/Btu$, or R7 in the trade)) was attached to the flue collar as specified by the ANSI/ASHRAE 103-1988 standard. The stack was positioned under an exhaust hood/vent pipe arrangement and the flue products were exhausted to the outside through the rooftop.

The test furnace was extensively instrumented as specified by the ANSI/ASHRAE 103-1988 [2]. In addition, two 24 gage, type K thermocouples were installed at the exit of the combustion blower upstream of the draft safeguard opening to obtain the approximate average flue gas temperature before the mixing of the flue gas with the air entering through the small draft safeguard opening. For the tracer gas tests, sampling and injection metal tubes 9.5 mm O.D.(3/8 in.) were installed. These included (1) one sampling tube inserted at the center of the exit of the combustion blower, (2) one sampling/injection tube with its end blocked and with four equally spaced holes 16 mm (5/8 in.) apart starting 8 mm (5/16 in.) from the blocked end in the side wall, inserted perpendicular to the center line of the test stack at 0.31 m (12 in.) downstream of the plane in the test stack where flue gas temperature is measured (see ANSI/ASHRAE 103-1988), (3) one sampling tube similar to the one in (2) but located at 0.15 m (6 in.)

upstream of the test stack exit, and (4) four tubes for injecting tracer gas at the inlet of each of the four serpentine heat exchangers and manifolded together. In addition, one tube was placed near the stack exit downstream of the sampling tube in (3) to act as a return port for the sampled gas. The gas samples during the tests were analyzed by a carbon dioxide (CO_2) and a carbon monoxide (CO) non-dispersive infrared gas analyzer. The CO_2 analyzer was calibrated with reference gas with known CO_2 concentrations of 2.922, 5.200, and 9.993 percent. The CO analyzer was calibrated with reference gas with known CO concentrations of 10.5, 79.37, and 394.8 ppm. During the test, the sample gas was passed through a beaker immersed in an ice-water mixture and a dryer to obtain the dry sample gas as specified in the ANSI/ASHRAE 103-1988.

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 micro-computer. The computer controlled the data scan rate by the use of an off-the-shelf data acquisition and control application software. Due to the large amount of data collected, the data recording rate varied from every 5 seconds during the periods when tracer gas was injected and gas samples were collected to every 30 seconds per recording during the non-tracer gas test period. Data were analyzed using a commercially available spreadsheet program.

4. TEST PLAN AND PROCEDURE

The tests were done in two phases. The first phase involves tests performed with the small vent spillage passage open during the cool-down portion of the test as specified in ANSI/ASHRAE 103-1988. The second phase was to treat the small vent spillage (draft safeguard) passage as an integral draft diverter so that the opening was blocked during the cool-down test as specified in ANSI/ASHRAE 103-1988 for unit with integral draft diverter. The test stack was insulated as described previously during the tests.

4.1 Preliminary test setting:

The test condition and switch setting for the furnace in this test were set according to the requirement of ANSI/ASHRAE 103-1988. The combustion blower post purge time was set to 0 for this test. The procedure for the preliminary setting is as follows:

1. Run the furnace with the vent spillage (draft safeguard) passage open until steady-state conditions are reached (about 45 minutes). Record the ignition time delay between the burner switch on time and the actual burner on time. Measure the flue gas temperature and flue gas carbon dioxide (CO_2) concentration at the combustion blower housing outlet. Also measure the stack gas temperature and the stack gas CO_2 inside the test stack at 0.3 m (12 in.) downstream of the flue collar. Measure the air-side temperature rise across the furnace heat exchanger (supply air minus return air), using the single thermocouple in the return side and the thermocouple grid in the supply side of the air ducts as specified in ANSI/ASHRAE 103-1988.

2. Turn off the burner to start the cool-down test. Monitor the air circulating fan for the time when the fan shuts off. Record this time. At the same time, monitor the air side temperature difference across the heat exchanger.

The temperature difference between the supply air and the inlet (return) air at the fan shut-off time should be 22.2 °C (40 °F). Adjust the control setting for the air circulating fan shut-off time delay to give this temperature difference.

3. The control setting for the air circulating fan time delay determined above was used in all the tests described below.

4.2 <u>Phase 1 - Vent spillage passage open during cool-down test</u>:

1. Run the furnace to steady-state conditions (45 minutes from burner-on). Record the gas temperature, carbon dioxide (CO_2) and carbon monoxide (CO) concentrations at both the combustion blower housing outlet and inside the test stack at the test plane (0.3 m (12 in.) downstream of the flue collar). The time-step between data scans was 30 seconds.

2. Start the 45-minute cool-down test by turning the burner off. Set the post purge time to 0 (turn combustion blower off at burner off). Start the injection of the tracer gas (carbon monoxide) with a certified known concentration at two minutes before the cool-down through the injection tube located at the test plane in the stack. At the same time, start sampling the tracer gas in the stack gas flow using the sampling tube located 0.15 m (6 in.) below the stack exit. Continue the tracer gas injection and sampling for the next 16 minutes, then stop the tracer gas injection and sampling but continue the cool-down test to the end of the 45 minutes. At the end of the 45 minutes cool-down period, start the cyclic test by turn on the burner-on switch for a 4-minute heat-up test. The time-step between data scans for this period was 5 seconds.

3. After the 4-minute heat-up test, turn the burner off and start the cyclic cool-down test for 14 minutes. Measure the background CO concentration inside the stack during this period. Data was scanned every 5 seconds.

4. At the end of the 14-minute cool-down test, turn on the burner-on switch for another 4-minute heat-up test. Start the injection of a tracer gas with a certified known concentration two minutes before the end of the 4-minute heat-up period. At the same time, start sampling the stack gas CO concentration at the stack exit location. Data was scanned every 5 seconds.

5. After the 4-minute heat-up test, turn the burner off and start another cool-down test for 14 minutes. Continue the injection and sampling of the tracer gas until the end of the 14-minute cool-down period. Stop the test at the end of this cool-down test. Data was scanned every 5 seconds.

6. Repeat the tests from step 1 through 5 for post purge times (delay times between the combustion blower off and burner off) of 5, 10, 15, 30, 90, and 180 seconds.

4.3 <u>Phase 2 - Vent spillage passage sealed during cool-down test</u>:

For the test furnace, the ratio of the net area of the vent spillage (draft safeguard) passage opening to the stack area is 0.098, or 9.8%, which is just below the 10% limit set in ANSI/ASHRAE 103-1988 for exemption from the sealing of an integral draft diverter opening during cool-down and cyclic tests. In the standard, a unit with an integral draft diverter is first tested with the diverter open during the steady-state test where the CO_2 concentration in the flue gas is measured at the outlet of the heat exchanger. The diverter is then sealed and the concentration of CO_2 in the flue gas is measured in a horizontal plane in the test stack (0.15 m upstream of the test stack exit plane) during another steady-state test. If the measured CO_2 concentration during this second steady-state test does not agree within ± 0.2 percentage points with the one measured at the heat exchanger exit during the first steady-state test, the exit area of the test stack shall be progressively restricted during this steady-state test until the agreement between the two measurements of CO_2 concentration is within ± 0.2 percentage points. The cool-down test, the heat-up test and the optional tracer gas test are then conducted with this last configuration (of sealed diverter opening and the restricted test stack exit area).

The purpose of the tests in this phase was to determine if the sealing of the draft relief opening during the cool-down and cyclic tests will show any significant difference in the off-cycle losses from the result obtained in the phase 1 test where the opening was not sealed. This test would also check whether it is valid in phase 1 above to conduct the tracer gas test (injection and sampling) in the test stack portion of the vent system when the draft relief opening is not sealed during the tracer gas test. The method for the tracer gas test recommended in ANSI/ASHRAE 103-1988 is to inject the tracer gas at the combustion chamber and to take a flue gas sample in a location upstream of a draft relief opening if it is not sealed during the test. The recommended procedure is harder to perform on the test furnace where tracer gas has to be injected into four heat exchanger (and flue gas) passages and the sampling tube is to be inserted through a very small draft relief opening. It is also less accurate due to possible uneven distribution of the tracer gas in the mass flow through the four heat exchangers. For the phase 2 tests, with the small vent opening sealed during these tests, injection and sampling of the tracer gas in the stack is equivalent to injection and sampling in the combustion chamber since there is no leak passage from the combustion chamber to the test stack exit in the vent system.

The procedure used to perform the phase 2 tests was as follows. After the small draft relief opening was sealed, the system was brought up to steady-state and the CO_2 concentration at the test stack was measured. The stack CO_2 was found to be within ± 0.2 percentage points of the flue CO_2 previously measured at the combustion blower exit (step 1 of phase 1 with the small draft relief passage open). This was within the range of accuracy specified in the test procedure [1,2] and hence the test stack was not restricted during the cool-down and heat-up tests. Tests were conducted following the same test sequence as in phase 1 (steps 1 through 5) with the post purge times set to 0, 15, 30, 60 and 90 seconds. No insulation on the combustion blower housing and the flue collector box was added since insulation on the front area of the blower housing could block the cooling air flow for cooling the blower motor.

The results from these tests were then compared with that of phase 1 described previously.

5. CALCULATION PROCEDURE

In all of the test results analyzed, the concentration value of the tracer gas, CO, in the sample was converted into the mass flow rate of the flue or the stack gas by the following equation:

$$M_{X,OFF} = [(C_I - C_T)/(C_T - C_B)] \cdot \rho \cdot V_T \quad (1)$$

where $M_{X,OFF}$ = mass flow rate of the flue (X=F) or stack (X=S) gas
C_I = CO concentration by volume of the injected tracer gas mixture
C_T = CO concentration by volume of the sample gas from the flow stream
C_B = background CO concentration by volume in the flow stream
ρ = density of gas at temperature T_T at the flow meter
V_T = volume flow rate of the injected tracer gas mixture

The off-cycle sensible heat loss rate, $Q_{S,OFF}$, at time t (counted from the start of the cool-down) was computed from the $M_{X,OFF}$ and the measured flue gas temperature (X=F) or stack gas temperature (X=S) by the following equation:

$$Q_{S,OFF} = C_P \cdot M_{X,OFF} \cdot (T_{X,OFF} - T_{RA}) \quad (2)$$

where $Q_{S,OFF}$ = off-cycle loss rate
C_P = specific heat capacity of air
$M_{X,OFF}$ = flue or stack gas mass flow rate from Eq.(1)
$T_{X,OFF}$ = measured flue (X=F) or stack (X=S) temperature at time t
T_{RA} = room ambient temperature

In the last equation, the total off-cycle sensible heat loss, $L_{S,OFF}$, expressed as a percent of the total input energy to the burner during the on-cycle period, is defined as:

$$L_{S,OFF} = [100/(Q_{IN} \cdot t_{ON})] \cdot \int_0^{t_{OFF}} Q_{S,OFF} \cdot dt \quad (3)$$

$$= [100/((Q_{IN} \cdot t_{ON})] \cdot (\Delta t/2) \cdot [Q_{S,OFF,1} + Q_{S,OFF,n} + 2 \cdot \sum_{i=2}^{n-1} Q_{S,OFF,i}] \quad (3a)$$

where t_{OFF} = length of the entire off-cycle period starting from burner off
= 13.3 minutes for furnaces
Q_{IN} = burner energy input rate
t_{ON} = assigned burner on-cycle time = 3.87 minutes for furnaces
Δt = time interval = 5 s
n = total number of time steps with interval Δt

The total percent off-cycle sensible heat loss, $L_{S,OFF}$, over the whole off-cycle period (13.3 minutes for furnaces as specified in ANSI/ASHRAE 103-1988) was obtained by summing up the values of $(Q_{S,OFF}) \cdot (\Delta t)$ in Eq. 2 at each time interval Δt (5 seconds for the present test series) for the 13.3 minutes period. The Trapezoidal rule of integration (eq. 3a) was used in this study.

6. TEST RESULTS

The results of the various tracer gas tests described in the previous section are shown and discussed below. Based on the test results, a test procedure using the tracer gas method is developed and recommended for evaluating the performance of power burner employing post purge.

6.1 Phase 1 test - Vent spillage passage open during cool-down:

The results of the tests conducted in Phase 1 with the small vent spillage passage open, showed a significant difference in the flue gas temperature and mass flow rate between test runs with and without post purge, especially when the post purge interval was greater than 10 seconds. Figures 2 and 3 show typical stack gas temperature and flow variations for the furnace tested without post purge and with 15, 30, 60, 90 and 180-second post purge interval. It is seen from Fig. 2 that immediately after the burner was shut-off, the temperature dropped at a faster rate with post purge than with no post purge. The mass flow rate shown in Fig. 3 actually increased during the post purge period while it decreased rapidly for the no post purge case. The changes in the mass flow rate between the with and the without post purge cases during the purging period were more significant than the changes in the temperature. From equation 2, the off-cycle sensible loss is a function of the product of the mass flow rate and the flue gas temperature rise above room temperature, and the off-cycle loss computed from test with post purge were greater than the zero post purge case. The longer the post purge period was, the larger the losses. This is shown in Table 1 where the total sensible loss during the off-cycle are computed from the measured temperature and mass flow rate data at 5-second interval and integrated over the entire off-cycle period for the post purge intervals of 0 (no post purge), 5, 10, 15, 30, 60, 90 and 180 seconds. Table 1 also shows the off-cycle sensible loss calculated on the basis of the existing ANSI/ASHRAE 103-1988 optional tracer gas procedure (and the existing DOE test procedure) where a single set of gas temperature and tracer gas concentration data, measured at 5.5 minutes after the burner was turned off, was used to compute the loss.

Table 1. Tracer gas measurement of off-cycle sensible loss for unit employing post purge - vent spillage passage open

Post purge (P.P.) interval sec.	Total off-cycle sensible loss - % Sum over entire off-cycle period	By existing ASHRAE 103-1988 procedure
0.	3.00	2.47
5.	3.15	2.44
10.	3.30	2.37
15.	3.52	2.34
30.	4.12	2.36
60.	4.68	2.12
90.	5.50	2.05
180.	6.92	1.85

In the above table, the second column is the measured sensible loss based on the 5-second temperature and tracer gas (flow rate) data. It is seen that the loss increases with increasing post purge time. The third column in the table is the calculated off-cycle sensible loss based on the existing optional tracer gas method described in ANSI/ASHRAE 103-1988 and the existing DOE test procedure. As mentioned in the previous paragraph, the current ASHRAE/DoE methods calculate the off-cycle losses from a single set of data of the flue gas temperature and tracer gas concentration measured at a time 5.5 minutes into the off-cycle after the burner shuts off. Since no post purge was considered in the development of this procedure, the flow was buoyancy driven and exponential decay of flue gas temperature was assumed to start right after the burner shuts off. As a result, for test runs with post purge, the changes in the temperature and mass flow rate from the "no post purge" condition caused by the operation of the combustion blower during the post purge interval were not taken into account. Comparing the values between column 2 and column 3, it is seen that the existing ASHRAE/DoE procedures result in very large errors for the off-cycle loss when the post purge interval is long. Since the system's annual fuel utilization efficiency (AFUE) is related to the value of the off-cycle loss (the smaller the loss, the larger the AFUE), the existing ASHRAE/DoE method gives an AFUE value larger than what it should be for systems employing long post purge time.

6.2 <u>Phase 2 test - Vent spillage passage sealed during cool-down</u>:

As stated previously, the phase 2 tests described in the Test Plan section was conducted to check the effect of the sealing of the small vent spillage passage on the measured off-cycle loss, and to verify the accuracy of the method used in phase 1 tests where the tracer gas tests were conducted in the test stack with the small vent passage kept open during the test. The results of the phase 2 tests are shown in Table 2 below. Results from the phase 1 tests are also included in the Table for a comparison between the two test conditions.

Table 2. Comparison of tracer gas measurement of off-cycle sensible loss for unit employing post purge -- vent spillage passage open vs sealed during the cool-down test

	Total off-cycle sensible loss - %	
Post purge (P.P.) interval - sec	with vent passage open	with vent passage sealed
0	3.00	3.17
15	3.52	3.74
30	4.12	4.18
60	4.68	4.88
90	5.50	5.70

The above Table 2 shows that the computed off-cycle sensible loss values with the small vent spillage (draft safeguard) passage open during cool-down test agreed within 0.2 percentage points with the values obtained with the small vent passage sealed during the cool-down test. This shows that the tracer gas test can be conducted during the cool-down test with the small vent passage open as currently allowed in the ANSI/ASHRAE 103-1988. As discussed in section 4 (second paragraph under Phase 2 Test) of this report, the procedure for tracer gas test recommended in the ANSI/ASHRAE 103-1988 is to inject and sample the tracer gas upstream of any draft relief opening. With the small vent spillage passage sealed in the phase 2 tests, the tracer gas test procedure conformed to the recommended procedure since there was no draft relief opening up to the end of the test stack. In the phase 1 tests, the test stack was, however, downstream of the open vent spillage passage and hence it was not in strict compliance with the recommended procedure. The good agreement between the results of the phase 1 and phase 2 tests shows that even with the small vent passage open, the tracer gas test can be conducted in the test stack where the injection of tracer gas and collection of flue gas sample are much easier to conduct, provided that the ratio of the net vent opening area to net test stack area is 10% or less as specified in ANSI/ASHRAE 103-1988.

As was described in the phase 1 test results above, there was a large difference in the value of the off-cycle losses determined by the tracer gas measured, integrated loss and those calculated from the existing ASHRAE 103-1988 optional tracer gas procedure. Examination of Figures 2 and 3 shows that, provided that the post purge period is less than one-fourth (1/4) of the off-cycle period, the flue gas temperature decreased at a nearly constant rate during the post purge interval, and that the mass flow rate increased from the steady-state value. The figures also show that after the post purge period, the temperature changed to the exponential decay pattern and the flow became buoyancy driven as in the case of operating the unit with no post purge. This indicates that the calculation of the off-cycle loss can be separated into two parts. The first part of the loss calculation is for the post purge interval where it is assumed that the temperature decreases linearly and that the volumetric flow rate of the combustion blower remains constant (mass flow rate increases with decreasing temperature). The simplified constant volumetric flow rate assumption eliminates the necessity of obtaining the performance curves of the combustion blower which is generally not available in the operation manual of a particular furnace. The second part of the loss calculation is for the period after post purge where the existing optional tracer gas method and calculation procedure for a power burner unit with no post purge as described in ASHRAE 103-1988 apply. The only change from that procedure is that the time variable must be shifted by an amount equal to the post purge interval. The total off-cycle loss will be the sum of the losses from the two parts. The following section describes the procedure for the calculation of the off-cycle loss during the post purge interval.

7. OFF-CYCLE LOSSES DURING POST-PURGE PERIOD

If it is assumed that the volumetric rate of flow through the combustion blower remains constant during both the burner-on and the post-purge periods when the blower is on, and the flue gas temperature decreases linearly during the post-purge period, the off-period sensible and infiltration losses can be derived as follows:

1. Assuming constant blower volumetric flow rate during the post-purge period:

$$V_{F,ON} = M_{F,ON}/\rho(T_{F,SS}) = M_{F,OFF}(t)/\rho(T_{F,OFF}(t))$$

or,

$$M_{F,OFF}(t) = M_{F,ON}\rho(T_{F,OFF}(t))/\rho(T_{F,SS}) \quad (4)$$

where: $M_{F,OFF}(t)$ = Flue gas mass flow rate during post-purge at time t
$M_{F,ON}$ = burner-on steady-state flue gas mass flow rate
ρ = flue gas density at temperature indicated
$T_{F,OFF}(t)$ = Flue gas temperature during post-purge at time t
$T_{F,SS}$ = burner-on steady-state flue gas temperature

The procedure for calculating the value of $M_{F,ON}$ is given in ASHRAE 103-1988.

Applying the perfect gas law,

$$M_{F,OFF}(t) = M_{F,ON}\cdot\rho(T_{F,OFF}(t))/\rho(T_{F,SS})$$

$$= M_{F,ON}\cdot(T_{F,SS} + 273.16)/(T_{F,OFF}(t) + 273.16) \quad (5)$$

2. Assuming linear flue gas temperature variation during post-purge period:

$$T_{F,OFF}(t) = T_{F,SS} - [(T_{F,SS} - T_{F,OFF}(t_P))/t_P]\cdot t \quad (6)$$

where: t_P = length of post-purge period
$T_{F,OFF}(t_P)$ = flue gas temperature at end of post-purge period

Applying the correction factor $C_{T,OFF}$ for burner shut-down cycling effect (and also the correction factor C_S' if outdoor air is used for combustion) to $(T_{F,OFF}(t)-T_{RA})$ as defined in section 11.2.9.14 (and section 11.2.9.15 for C_S') of ASHRAE 103-1988 [2]:

$$T_{F,OFF}(t) - T_{RA} = C_{TS}\cdot[(T_{F,SS} - T_{RA}) - ((T_{F,SS} - T_{F,OFF}(t_P))/t_P)\cdot t]$$

or,

$$T_{F,OFF}(t) = T_{RA} + C_{TS}\cdot[(T_{F,SS} - T_{RA}) - ((T_{F,SS} - T_{F,OFF}(t_P))/t_P)\cdot t] \quad (7)$$

where: T_{RA} = room air temperature
$C_{TS} = C_{T,OFF}$ for indoor combustion air
$= C_S'\cdot C_{T,OFF}$ for outdoor combustion air
$C_{T,OFF}$ = burner shut-down cycling effect correction factor as defined in section 11.2.9.14 of ASHRAE 103-1988 (see also Ref.3)
C_S' = 1.22 = correction factor for effect of outdoor air passing through the heat exchanger during the off-period as defined in section 11.2.9.15 of ASHRAE 103-1988

Value of $C_{T,OFF}$ will be calculated by using the flue gas temperature data measured during the off-period after the post-purge as specified in ASHRAE 103-1988.

3. Sensible loss during post-purge period:

The total off-period sensible loss is the sum of the product of the heat capacity, flow rate and the temperature difference between the flue gas and the room air. For the post-purge period, the sensible loss is calculated as,

$$L_{S,purge} = C_P \int_0^{t_P} M_{F,OFF} \cdot [T_{F,OFF}(t) - T_{RA}]dt$$

$$= C_P \cdot M_{F,ON}(T_{F,SS} + 273.16) \int_0^{t_P} [(T_{F,OFF}(t) - T_{RA})/(T_{F,OFF}(t) + 273.16)] \cdot dt$$

Substituting $(T_{F,OFF}(t)-T_{RA})$ and $T_{F,OFF}(t)$ from Eq. 7 to the above equation, expressing the loss as a percent of the energy input during the on-period, and integrating the resulting equation yield:

$$L_{S,OFF,purge} = 100 \cdot L_{S,purge}/(60 \cdot Q_{IN} \cdot t_{ON})$$

$$= 100 \cdot C_P \cdot M_{F,ON} \cdot t_P \cdot (T_{F,SS} + 273.16) \cdot [1/(t_{ON} \cdot Q_{IN} \cdot 60)] \cdot$$

$$\{1 + \frac{T_{RA} + 273.16}{C_{TS}[T_{F,SS} - T_{F,OFF}(t_P)]} \cdot \ell n[\frac{T_{RA} + 273.16 + C_{TS} \cdot [T_{F,OFF}(t_P) - T_{RA}]}{T_{RA} + 273.16 + C_{TS} \cdot [T_{F,SS} - T_{RA}]}]\} \qquad (8)$$

4. Infiltration loss during post-purge period for units using indoor air for combustion:

The total off-period infiltration loss is the sum of the product of the heat capacity, flow rate, and the temperature difference of the room air and the outdoor air. For the post-purge period, the infiltration loss is calculated as,

$$L_{I,purge} = C_P \int_0^{t_P} M_{F,OFF}(t) \cdot (T_{REF} - T_{OA}) \cdot dt$$

$$= C_P \cdot (T_{REF} - T_{OA}) \cdot M_{F,ON} \cdot (T_{F,SS} + 273.16) \int_0^{t_P} [1/(T_{F,OFF}(t) + 273.16)] \cdot dt$$

where: T_{REF} = a reference room air temperature = 21.1 °C
T_{OA} = national average outdoor air temperature = 5.55 °C

Substituting the expression for $T_{F,OFF}$ from Eq. 7 to the above equation, expressing the loss as a percent of the on-period energy input, and integrating the resulting equation yield:

$$L_{I,OFF,purge} = 100 \cdot L_{I,purge}/(60 \cdot Q_{IN} \cdot t_{ON})$$

$$= 100 \cdot C_P \cdot M_{F,ON} \cdot t_P \cdot (T_{F,SS} + 273.16) \cdot \varsigma \frac{T_{REF} - T_{OA}}{C_{T,OFF} \cdot [T_{F,SS} - T_{F,OFF}(t_P)]}]\!] \cdot$$

$$\ell n[\frac{T_{RA} + 273.16 + C_{T,OFF} \cdot [T_{F,SS} - T_{RA}]}{T_{RA} + 273.16 + C_{T,OFF} \cdot [T_{F,OFF}(t_P) - T_{RA}]}]\!] \cdot [1/(60 \cdot Q_{IN} \cdot t_{ON})] \qquad (9)$$

Note that for units that use outdoor air for combustion, $L_{I,OFF,purge} = 0$.

It should be noted that the above derivation is based on the assumption of a linear temperature variation during the post purge interval so that only two measured temperatures (at the beginning and end of the interval) are needed. As shown in Figure 2, the longer the post purge interval lasts, the greater the temperature deviates from the linear assumption. Therefore, the above derivation is valid only for a post purge interval of less than 3 minutes for furnaces. However, it is felt that for a well designed gas-fired unit, there is no reason to have a post purge interval longer than a few seconds. For a well designed oil-fired unit, a post purge period of 20 to 30 seconds is likely to be sufficient. Hence the above derivation should be applicable to units with a "reasonable" post purge time interval.

8. OFF-CYCLE LOSSES DURING PERIOD FOLLOWING POST-PURGE

When the combustion blower is turned off at the end of the post-purge period, the change in the flue gas temperature reverts to an exponential decay pattern and the flow becomes buoyancy driven. The calculation procedure for the off-period sensible and infiltration losses for this type of flow, is the same as that presented in References 2 to 4. Using the optional tracer gas method in ANSI/ASHRAE 103-1988, a one point measurement of the flue gas temperature and the tracer gas concentration 5.5 minutes after the post-purge period ended is used to determine a flue draft factor D_F for the calculation of the losses during this period. The only change from the procedure is that the time variable is shifted by an amount equal to the length of the post purge interval. For example, the length of the off-period in the calculation procedure is reduced to $(t_{OFF} - t_P)$ where t_{OFF} is the total off-cycle period and t_P is the length of the post purge period as defined in section 7 above. Also, the time intervals (from burner off) in the measurement of the flue gas temperatures during the cool-down test for the calculation of the off-cycle time constant are increased by t_P. (e.g., the times specified for measuring the flue gas temperatures to determine the off-cycle time constant are $t_3 = (t_P + 1.5)$ min., $t_4 = (t_P + 9)$ min., and the tracer gas measurements are made between $(5 + t_P)$ and $(6 + t_P)$ minutes after the burner is shut off.)

9. COMPARISON OF RESULTS AND DISCUSSION

Using the equations in section 7 above for the post-purge period and the calculation procedure of ANSI/ASHRAE 103-1988 (as discussed in section 8 above) for the period after post-purge, the off-cycle sensible loss for the tests in phase 1 (see section 4) were computed. The following paragraphs discuss the results of these calculations.

Table 3 shows the results of the computed off-cycle sensible loss (labelled as Recommended analytical solution) for the entire off-period using the equations derived analytically in section 7 above and the procedure discussed in section 8 above. The integrated results from the tracer gas measurement described in section 6.1 are also shown for comparison.

Table 3. Comparison - tracer gas measured vs. recommended analytical results

	Off-cycle sensible loss - (%)					
Post-purge (P.P.) Interval (sec)	Integrated tracer gas result			Recommended analytical solution		
	During P.P.	After P.P.	Total	During P.P.	After P.P.	Total
0	0.00	3.00	3.00	0.00	2.47	2.47
5	0.20	2.95	3.15	0.19	2.38	2.57
10	0.41	2.89	3.30	0.39	2.26	2.65
15	0.63	2.89	3.52	0.56	2.21	2.77
30	1.25	2.87	4.12	1.10	2.12	3.20
60	2.42	2.26	4.68	2.02	1.74	3.76
90	3.50	2.01	5.51	2.92	1.53	4.45
180	5.68	1.24	6.92	5.10	0.89	5.99

From the above table, it is seen that the results (last column labeled "Total") from the recommended analytical solution are much closer to the total integrated tracer gas measured results than those calculated from the existing procedure in ANSI/ASHRAE 103-1988 as presented in the third column in Table 1. However, there is still some deviations between the integrated tracer gas and recommended analytical results, ranging from 0.53 percentage points at 0 post purge time to 1.06 percentage points at 90 second post purge time. Table 4 below shows the individual differences during post purge, after post purge, and the sum of the two periods.

Table 4. Differences - (tracer gas measured minus recommended analytical results)

Post-purge (P.P.) Interval (sec)	Differences in off-cycle sensible loss - (%) (Tracer gas result) minus (Recommended analytical result)		
	During P.P.	After P.P.	Total
0	0.00	0.53	0.53
5	0.01	0.58	0.59
10	0.02	0.63	0.65
15	0.07	0.68	0.75
30	0.15	0.75	0.90
60	0.40	0.52	0.92
90	0.58	0.48	1.06
180	0.58	0.35	0.94

The differences between the two results during the post purge interval were small for short post purge time intervals but became larger for the longer intervals. This is probably caused by the assumptions of linear flue gas temperature variation and constant volumetric flow rate through the combustion blower during this period. Figure 4 shows the measured volumetric concentration of the tracer gas (CO) during the off-cycle with a post purge time interval of 90 seconds. It is seen that during the post purge interval (first 90 seconds), the volumetric concentration of the tracer gas maintained a fairly constant value except a slight decrease at the beginning of the off-cycle. This indicates that the volumetric flow rate of the flue gas increased slightly from its on-period value before levelling off to a fairly constant value. Figure 4 also shows that during the post purge period where the flow rate was high, the tracer gas concentration was between 60 ppm and 70 ppm which was less than 1/5 of the full scale value of the CO analyzer (full scale was 500 ppm for the analyzer used in this experiment). Since a 2 % instrument accuracy at full scale could result in a ±10 % error at the low side (1/5 full scale) of the analyzer's full scale range, the measured tracer gas concentration and hence flue gas flow rate can have an error of 10 % during the post purge interval. Figures 5 and 6 show an example of a comparison of the measured and the calculated (by the recommended analytical method) gas temperature and mass flow rate, respectively, of the entire off-cycle period during the cyclic operation of the burner. It can be seen that the calculated gas temperature and the calculated mass flow rate are both lower than their respective measured values, resulting in a lower calculated loss. However, as shown in Table 4, the differences are small for post purge intervals of less than 30 seconds which are likely to be more than enough for typical post purge purpose. Also, post purge intervals longer than 30 seconds are unlikely if the recommended analytical method is adopted because a longer interval will only increase the calculated off-cycle losses and reduce the value of AFUE.

Table 4 also shows that the differences between the tracer gas measured and the recommended analytical method remain fairly constant (0.48 to 0.75 percentage points) during the period after post purge has ended. This is probably caused by measurement errors due to the rapid changing mass flow rate of the flue gas after the combustion blower is shut off right after the post purge ended. The slow response of the tracer gas instrument and the low tracer gas concentration (due to high flue gas flow) make the measurement of the mass flow rate less accurate at the beginning of this period, resulting in errors for the integrated result. The recommended analytical method for this period employs the measured data of the tracer gas concentration and gas temperature at one point to calculate the loss by analytical means. At that point (5.5 minutes after the combustion blower is shut off) the variation of the mass flow rate is much slower, the flow rate is much smaller and the tracer gas concentration in the flue gas is much higher and easier to measure, resulting in a more accurate prediction of the mass flow rate and off-cycle loss. Therefore, the difference is likely to be the result of error in the integrated tracer gas calculation caused by the inaccuracy in the measurement of a rapid changing and high flue gas flow. This is shown in Table 5 below. Table 5 shows the partial sum of the off-cycle losses calculated by the two methods for the initial intervals of 30 seconds following the post purge period. It also shows the differences in the losses between the two methods for this 30 seconds interval as well as for the whole period following post purge (values taken from Table 4). The last column in Table 5 gives the difference in the first 30 seconds as a percent of the total difference between the two methods over the whole period following post purge. It is seen that during the first 30 seconds following post-purge, the difference between the two methods amounts to about 36 to 52 percent of the total differences over the whole period (13.3 minutes with no post purge to 10.3 minutes with 180 seconds post purge for a gas-fired unit). That is, a large portion of the difference between the two methods occurs in the first 5% of the off-cycle period following post purge. Because of the uncertainty of the integrated tracer gas method in this initial period, it is felt that the result from the calculation based on analytical procedure involves less error and is more reliable, and hence the analytical procedure is the preferred method.

Table 5. Partial sum of off-cycle sensible losses for the first 30 seconds following post purge for the tracer gas measured and the recommended analytical method

	Partial sum (over first 30 sec.) off-cycle sensible loss following post purge period - (%)				30-second diff. as a percent of the diff. over the total period (%)
Post-purge (P.P.) (sec)	Tracer gas result	Recomm. analy. result	Difference (over 30 s)	Difference (total period)	
0	0.542	0.272	0.273	0.53	52
15	0.518	0.258	0.260	0.68	38
30	0.543	0.254	0.289	0.75	39
60	0.402	0.215	0.187	0.52	36
90	0.385	0.186	0.199	0.48	41
180	0.243	0.135	0.108	0.35	31

In summary, the test results show that the existing ANSI/ASHRAE 103-1988 optional tracer gas procedure under-estimated the off-cycle losses of a power vented furnace that employs post purge after the burner was shut off (see Table 1). The results also show that a recommended analytical procedure where the off-cycle losses were calculated separately for the post purge interval and the after-purge interval of the off-cycle, gave good agreement with the integrated loss over the off-cycle based on temperature and tracer gas concentration data measured at five second intervals. This indicates that the recommended analytical procedure derived here can be used to evaluate the off-cycle losses of a power vented furnace employing post purge after the burner is shut off, provided that the post purge interval is less than 1/4 of the total off-cycle period as for the test furnace. However, if for some reason the unit is designed to have a post purge interval longer than 1/4 of the total off-cycle period so that the flue gas temperature can no longer be approximated as linear over the long post purge interval, the interval can be divided into a number of equally timed sub-intervals of 1 to 2 minutes each with linearized temperature variation within each sub-intervals, and Eqs. 8 and 9 can be applied to each sub-intervals successively. In this case, additional temperature data, i.e., at the end of each sub-intervals, would be required during the post purge period.

10. CONCLUSIONS

A power vented gas-fired furnace employing a post purge period after the burner was shut off was tested using the tracer gas method for the determination of the off-cycle sensible loss. The integrated off-cycle loss over the entire off-period was computed using tracer gas concentration and flue gas temperature data collected at five (5) second intervals. The existing optional tracer gas method described in ANSI/ASHRAE 103-1988 [2] was used to calculate the same loss and was found to under-estimate the off-cycle loss and to give significant error with longer post purge intervals. A new (labeled as "recommended") analytical procedure was developed to correct the deficiency in the existing procedure. The new procedure separated the calculation into two parts. The first part dealt with the interval during the post purge period where a constant volumetric flow rate and a linear temperature variation of the flue gas were assumed. An analytical solution for the off-cycle losses was derived using the measured flue gas temperatures at the beginning and end of the post purge interval. The second part of the calculation dealt with the remaining portion of the off-cycle after the power vent blower (combustion blower) was shut off. The calculation for the second part used the optional tracer gas method and the same analytical procedure as described in the existing ANSI/ASHRAE 103-1988 procedure with only an offset in the appropriate time intervals (equal to the post purge time length). The total off-cycle sensible loss was the sum of the losses computed from the two periods. Results calculated from the new analytical procedure gave reasonably good agreement with the integrated results from tracer gas measurement. The new analytical procedure is simple to apply during the performance test of the furnace since only two additional pieces of data, the flue gas temperature at the end of the post purge interval and the length of the post purge time interval, are needed for the calculation. It is recommended that the new procedure should be incorporated into the DoE furnace/boiler test procedure [1] and the ANSI/ASHRAE 103-1988 calculation procedure for computing the off-cycle losses of power vented units employing post purge. The only limitation is that, because of the linear flue gas temperature approximation during the post purge period used in the derivation, the length of the post purge time interval should be no longer than 1/4 of the total off-cycle period as is for the test furnace. (If for some reason it is determined that units are being designed to have post purge intervals longer than 1/4 of the total off-cycle period so that the flue gas temperature can no longer be approximated as linear over the long post purge interval, the proposed procedure could be easily amended so that the post purge interval is divided into a number of equally timed sub-intervals of 1 to 2 minutes each with linearized temperature variation within each sub-intervals, and Eqs. 8 and 9 can be applied to each sub-intervals. However, additional temperature data, i.e., at the end of each sub-intervals, would be required during the post purge period.)

11. 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", Final Rule, March 28, 1984

2. ANSI/ASHRAE Standard 103-1988, "Methods of Testing for Annual Fuel Utilization Efficiency of Residential Central Furnaces and Boilers". ASHRAE, Atlanta, GA

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.

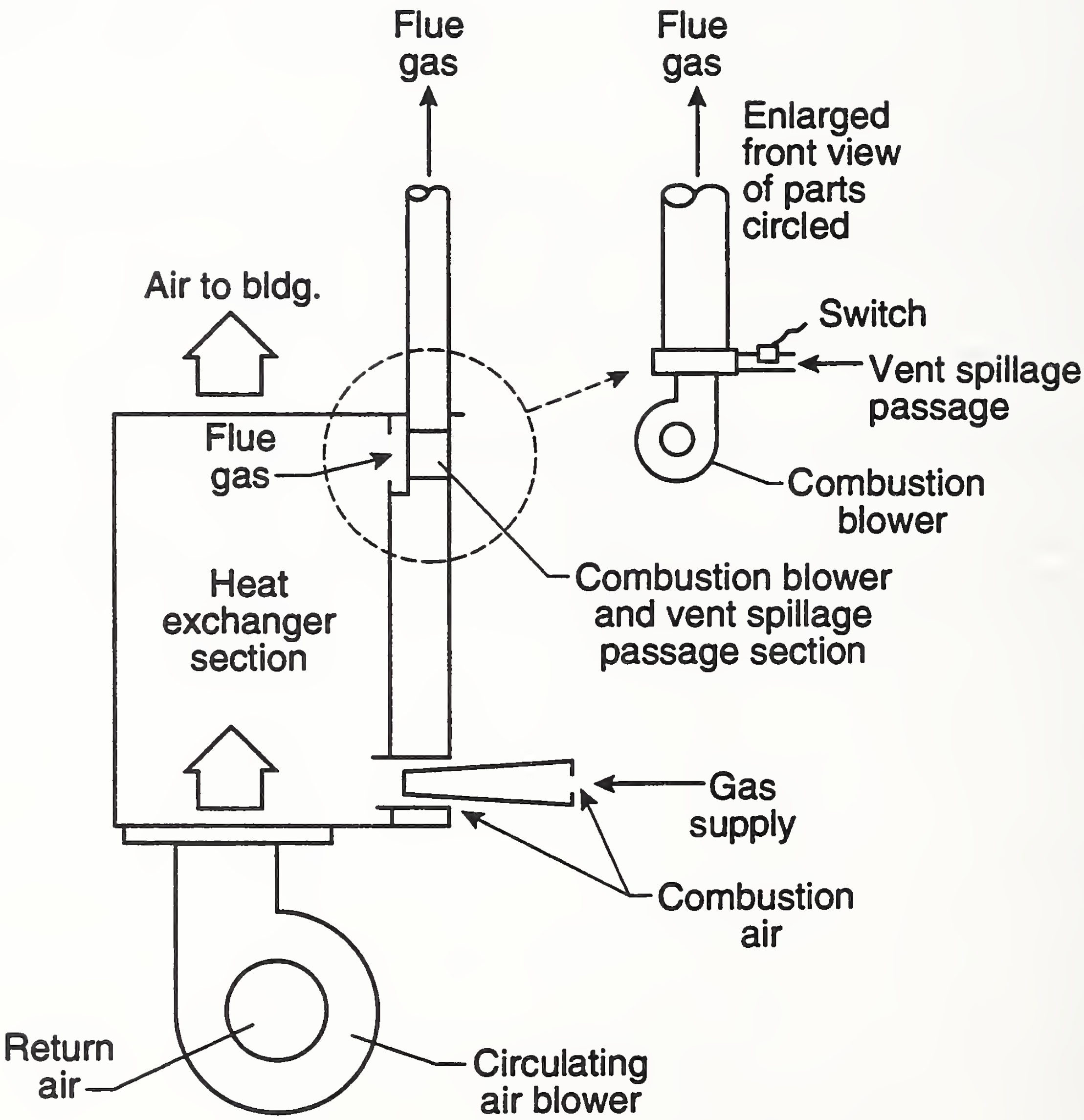

Figure 1 Schematic of the induced draft gas furnace

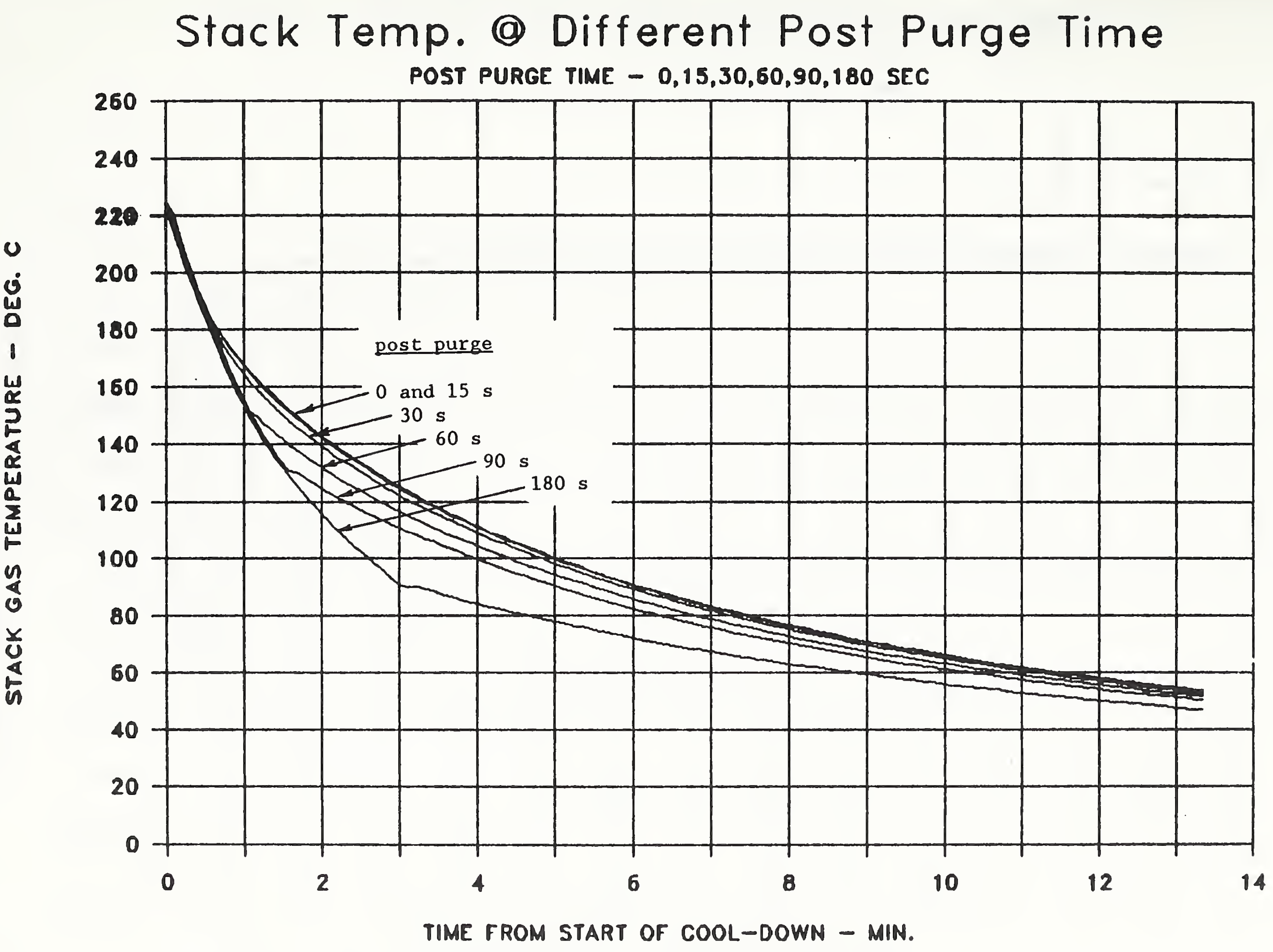

Figure 2 Variations of stack gas temperature with different length of post purge intervals during cool-down period

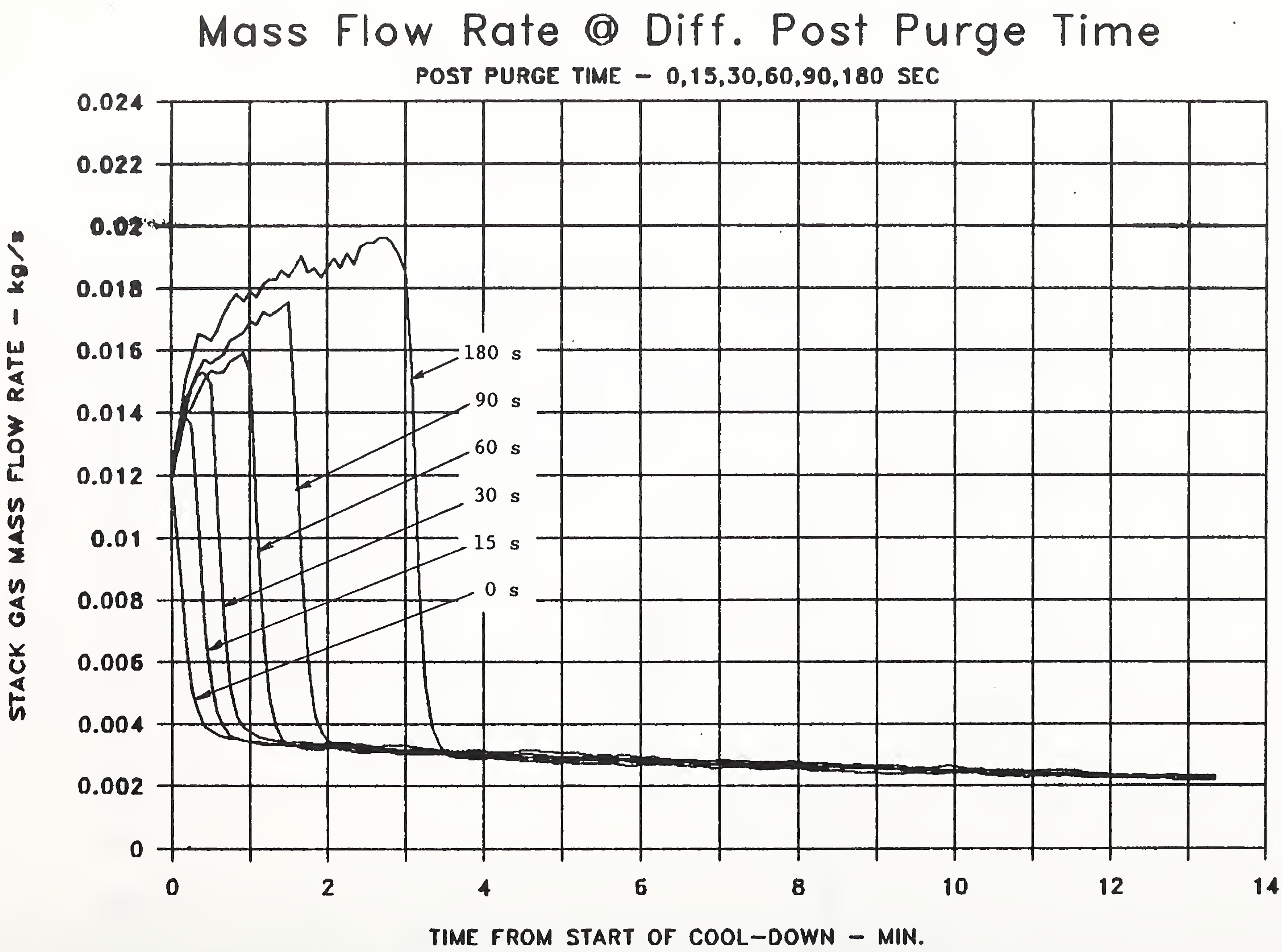

Figure 3 Variations of stack gas mass flow rate with different length of post purge intervals during cool-down period

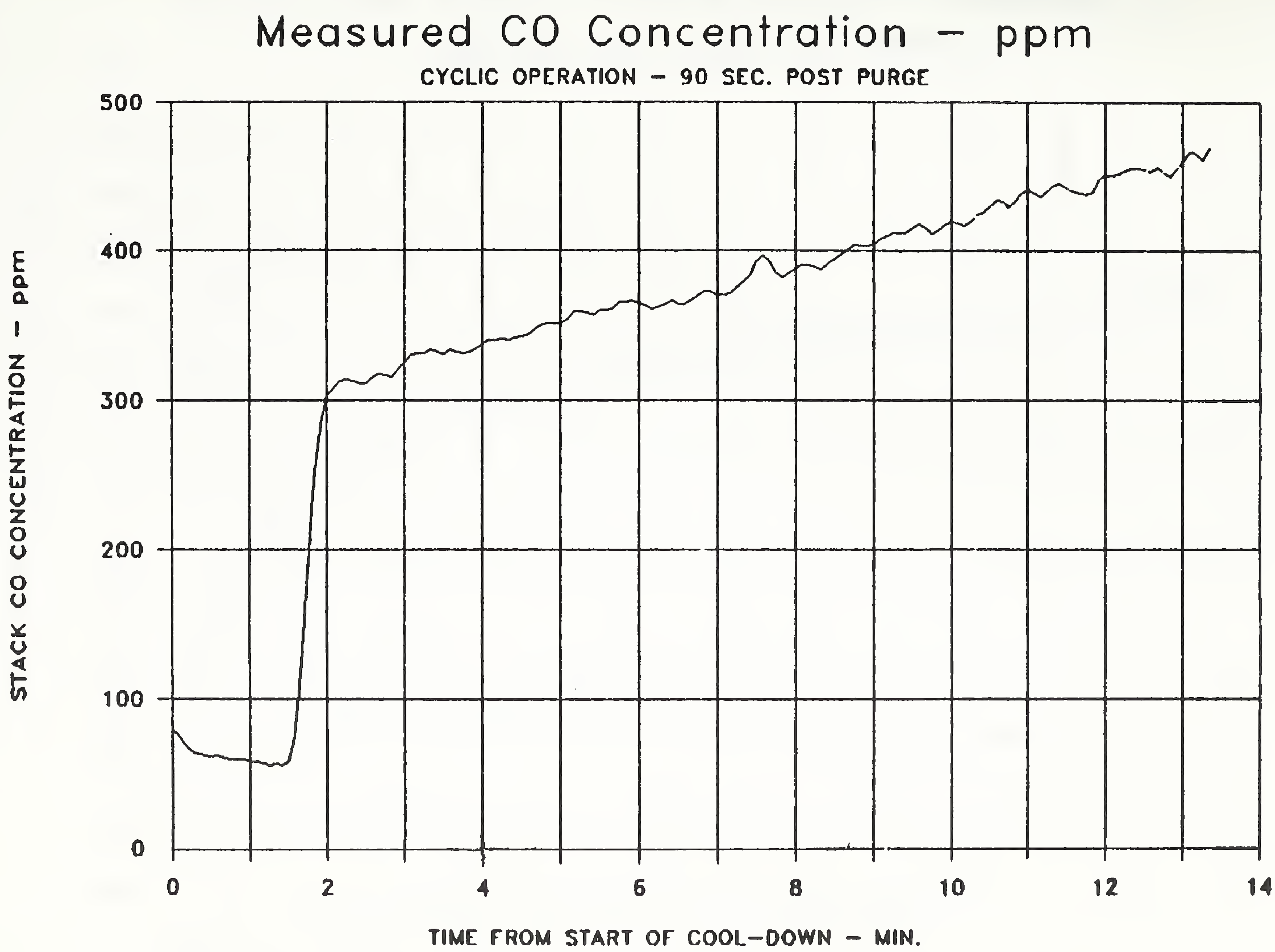

Figure 4 Variation of tracer gas concentration during cool-down period (post purge interval - 90 s)

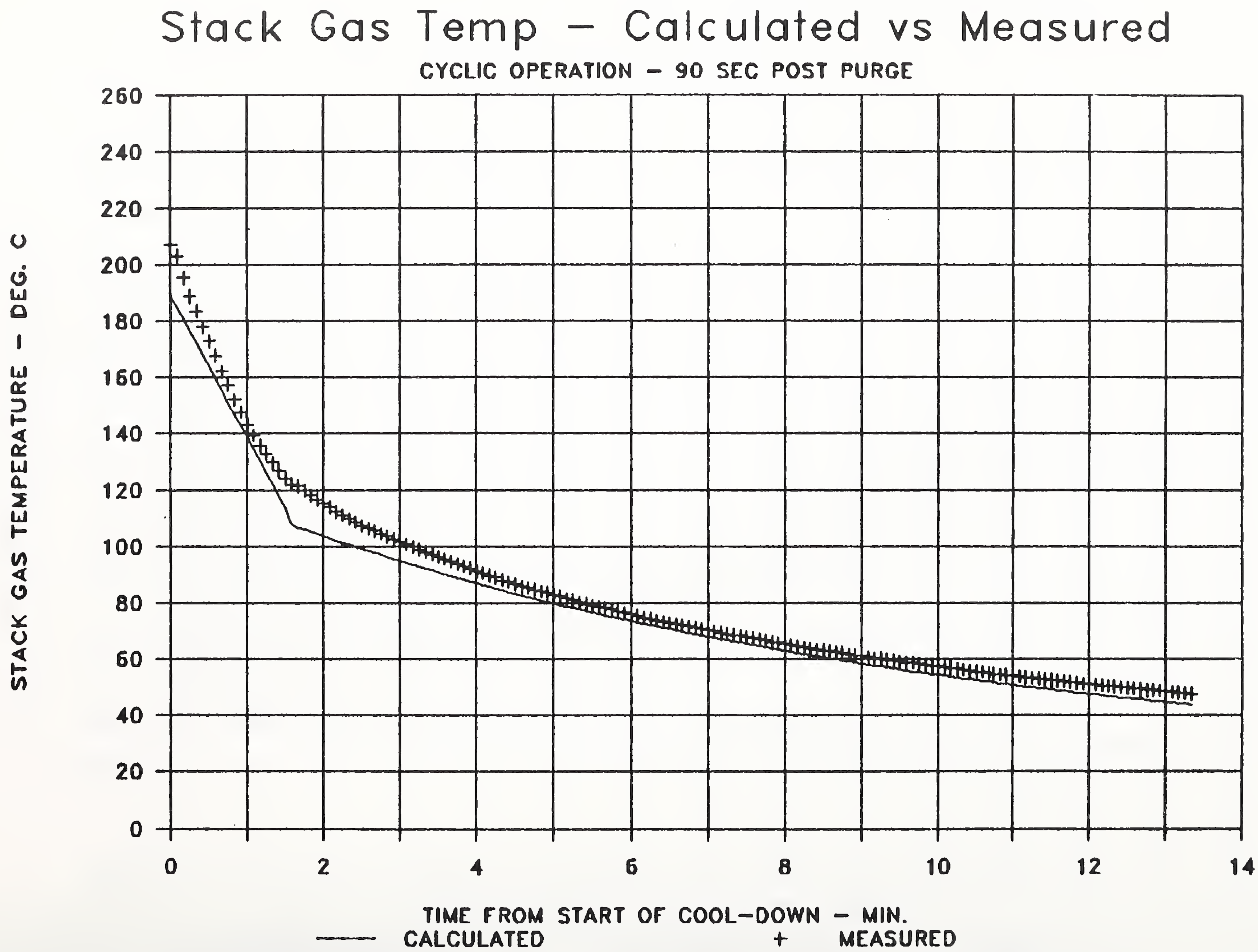

Figure 5 Comparison of calculated and measured stack gas temperatures during cool-down period (post purge interval - 90 s)

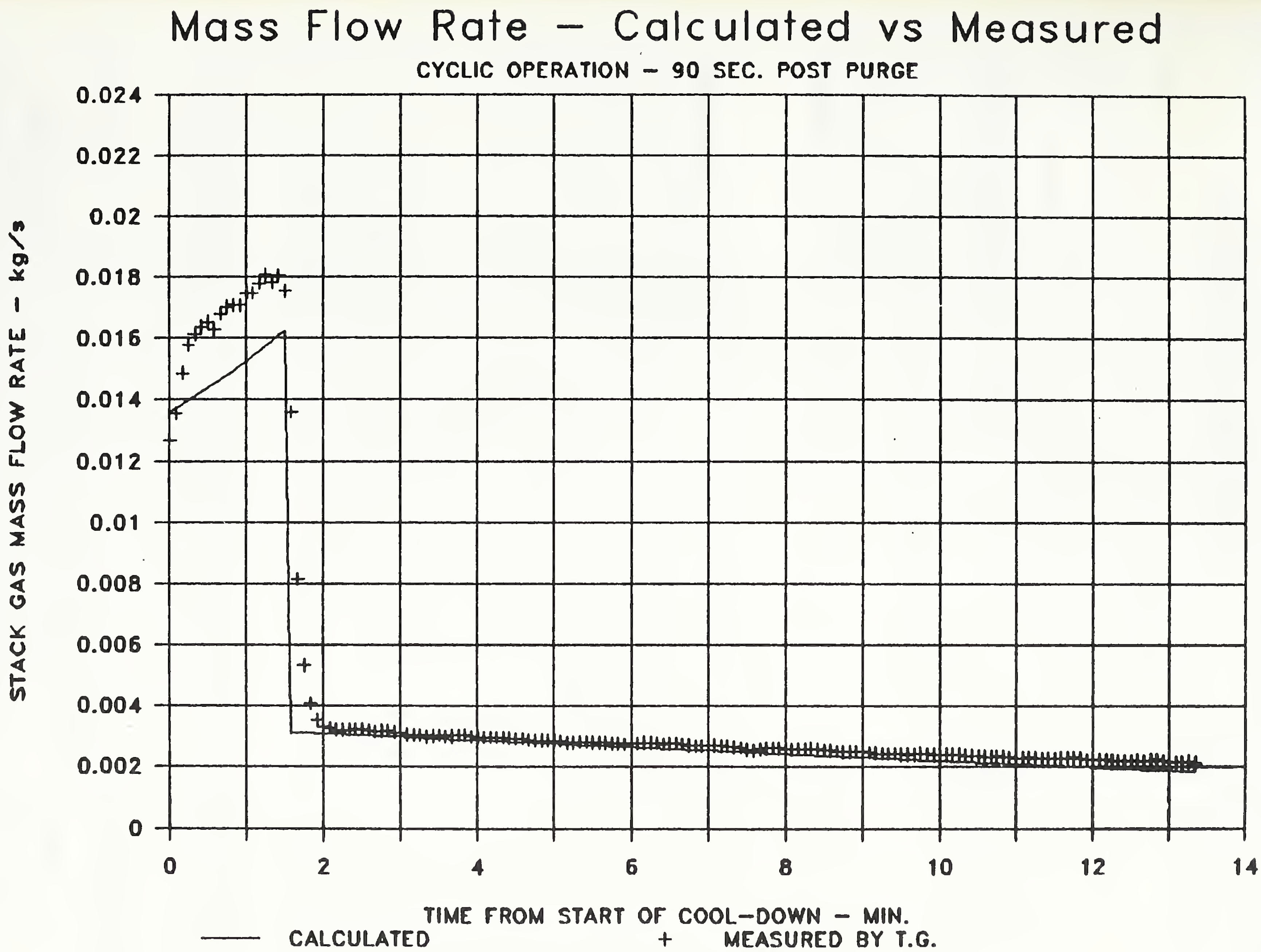

Figure 6 Comparison of calculated and measured stack gas mass flow rates during cool-down period (post purge interval = 90 s)

NIST-114A
(REV. 3-90)

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

BIBLIOGRAPHIC DATA SHEET

1. PUBLICATION OR REPORT NUMBER
NISTIR 4908

2. PERFORMING ORGANIZATION REPORT NUMBER

3. PUBLICATION DATE
AUGUST 1992

4. TITLE AND SUBTITLE
Evaluating the Off-Cycle Losses of a Gas-Fired, Power-Vented Furnace Employing Post Purge

5. AUTHOR(S)
Stanley T. Liu, George E. Kelly, and Charles P. Terlizzi

6. PERFORMING ORGANIZATION (IF JOINT OR OTHER THAN NIST, SEE INSTRUCTIONS)
U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
GAITHERSBURG, MD 20899

7. CONTRACT/GRANT NUMBER

8. TYPE OF REPORT AND PERIOD COVERED

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (STREET, CITY, STATE, ZIP)
Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

10. SUPPLEMENTARY NOTES

11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

A gas-fired, induced draft furnace employing post purge for venting after the burner shut off was tested by using a continuous tracer gas measurement technique over the entire off-cycle to determine the off-cycle sensible loss for various durations of post- purge. The results were compared with those obtained by the existing optional tracer gas method described in ANSI/ASHRAE Standard 103-1988. The existing optional tracer gas procedure uses tracer gas data obtained at one prescribed time in the off-cycle along with an analytical procedure to calculate the loss. This optional procedure was found to under-estimate the off-cycle loss and to give significant error with longer post purge durations. A new analytical procedure was developed to correct the deficiency in the existing procedure. The new procedure divides the off-cycle period into two intervals. The loss during the purging interval was calculated analytically by assuming a linear variation of the flue gas temperature and a constant volumetric flow rate of the flue gas. The loss during the interval after post-purge was calculated by the existing optional tracer gas procedure where the prescribed time to measure the one point tracer gas data was delayed by the length of the post-purge interval. The total off-cycle loss calculated by the new procedure gave reasonably good agreement with the integrated results from the continuous tracer gas measurement technique over the entire off-cycle. The new procedure is simpler to apply than the one using the continuous tracer gas measurement and requires only a small increase in the data taking effort and some minor revision of the existing test and calculation procedures.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)
ANSI/ASHRAE 103; burner off-cycle; calculation procedure; DOE test procedure; furnace/boiler test; off-cycle loss; performance test; post purge; power-vented burner; tracer gas test

13. AVAILABILITY

- [X] UNLIMITED
- [ ] FOR OFFICIAL DISTRIBUTION. DO NOT RELEASE TO NATIONAL TECHNICAL INFORMATION SERVICE (NTIS).
- [ ] ORDER FROM SUPERINTENDENT OF DOCUMENTS, U.S. GOVERNMENT PRINTING OFFICE, WASHINGTON, DC 20402.
- [X] ORDER FROM NATIONAL TECHNICAL INFORMATION SERVICE (NTIS), SPRINGFIELD, VA 22161.

14. NUMBER OF PRINTED PAGES
30

15. PRICE
A03

ELECTRONIC FORM