

# Improving Gas Furnace Performance: A Field and Laboratory Study at End of Life

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*Partnership for Advanced Residential Retrofit*

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## **Improving Gas Furnace Performance: A Field and Laboratory Study at End of Life**

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The work presented in this report does not represent performance of any product relative to regulated minimum efficiency requirements.

The laboratory and/or field sites used for this work are not certified rating test facilities. The conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.

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## **Acknowledgments**

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## Definitions

AE	Annualized efficiency
AFUE	Annual fuel utilization efficiency
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEopt™	Building Energy Optimization software
Btu	British thermal unit
DOE	U.S. Department of Energy
ESP	External static pressure
HVAC	Heating, ventilation, and air conditioning
HVAC SAVE	HVAC System Adjustment & Verified Efficiency
kWh	Kilowatt hour
MEEA	Midwest Energy Efficiency Alliance
w.c.	Water column

## Executive Summary

In 2010, natural gas provided 54% of total residential space heating energy in the United States on a source basis, or 3.5 quadrillion Btu, according to the U.S. Department of Energy (DOE) Building Energy Data Book. Natural gas burned in furnaces accounted for 92% of that total, and boilers and other equipment made up the remainder. A better understanding of installed furnace performance is key to energy savings for this significant energy use.

Natural gas furnace performance can be measured in many ways. The DOE annual fuel utilization efficiency (AFUE) rating provides a fixed value under specified conditions, analogous to the U.S. Environmental Protection Agency miles per gallon rating for new vehicles. The AFUE rating is provided by the manufacturer to the consumer and is a way to choose between models tested on the same basis. This value is commonly used in energy modeling calculations. ASHRAE 103 is a consensus furnace testing standard developed by the engineering community. The procedure provided in the standard covers heat-up, cool-down, condensate heat loss, and steady-state conditions and an imposed oversize factor. The procedure can be used to evaluate furnace performance with specified conditions or with some variation chosen by the tester. In this report the ASHRAE 103 test result will be referred to as *annualized efficiency* (AE) to avoid confusion with the DOE rating, and any nonstandard test conditions will be noted. Aside from these two laboratory tests, steady-state or flue loss efficiency can be measured in the field under many conditions, typically as found or tuned to the manufacturers' recommended settings. In this report, AE and steady-state efficiency are used as measures of furnace performance.

Modeled pre-retrofit energy consumption and retrofit energy savings commonly exceed those of actual energy consumption and savings. This is especially true in homes that are leaky, poorly insulated, and that have older mechanical systems (Polly et al. 2011). The discrepancy may be related to poor load modeling that increases runtimes; to the performance of equipment tested under laboratory conditions, which differs from field performance; or to equipment performance that degrades with time. The latter two theories are tested in this study.

The objective of this project is to examine the impact that common installation practices and age-induced equipment degradation may have on the installed performance of natural gas furnaces over the life of the product, as measured by steady-state efficiency and AE. The Partnership for Advanced Residential Retrofit identified 12 furnaces of various ages and efficiencies that were operating in residential homes in the Des Moines, Iowa, metropolitan area and worked with a local heating, ventilation, and air conditioning contractor to retrieve furnaces and test them for steady-state efficiency and AE in the lab. Prior to removal, system airflow, static pressure, equipment temperature rise, and flue loss measurements were recorded for each furnace as installed in the house. After removal from the field, the furnaces were transported to the Gas Technology Institute laboratory, where the Partnership for Advanced Residential Retrofit conducted steady-state efficiency and AE testing. Nine of the 12 furnaces could be tested in the lab with minor component repair that did not impact efficiency. Steady-state efficiency was calculated for each furnace from the field data. Each furnace was then tested for steady-state efficiency and AE under field conditions and AE under test conditions specified in the ASHRAE 103-2007 (consensus) test standard, based on furnace type. In this report, rated AFUE is used as the “before” condition and AE under ASHRAE Standard 103 conditions is used as the “after”

condition in the absence of individual furnace efficiency lab test results when the furnaces were new.

The test results show that steady-state efficiency in the field was 6.4% lower than that measured for the same furnaces under Standard 103 conditions in the lab, which included tuning the furnace input and airflow rate to the conditions recommended by the manufacturer. This value is based on the average of nine of the 12 furnaces that could be tested after minor repair.

Comparing AE measured under Standard 103 conditions with the rated AFUE shows similar values, implying that equipment performance did not significantly decrease over 15–24 years of operation. The conclusion is that rated AFUE values can be used as a good indicator of the performance of natural gas furnaces throughout their useful lives if they are installed according to the manufacturers' installation instructions. Installing a furnace correctly in the lab or in the field is a key driver in this finding: increase the blower speed to provide the correct airflow to match the manufacturer's recommended temperature rise without exceeding the manufacturer's design static pressure. If the fan speed cannot be adjusted properly, changes to the duct system will need to be made.

# 1 Problem Statement

## 1.1 Introduction

Natural gas furnaces are rated for efficiency using the U.S. Department of Energy (DOE) annual fuel utilization efficiency (AFUE) test standard under controlled laboratory test conditions. In the home, these furnaces are then installed under conditions that can vary significantly from the standard, require adjustment by the installing contractor to adapt to field conditions, may or may not be inspected over their useful lifetimes, and can operate with little maintenance over a 30-year period or longer. At issue is whether the installation practices, field conditions, and wear over the life of the furnace reduce the efficiency significantly from the rated efficiency. In this project, nine furnaces, with 15–24 years of field service, were removed from Iowa homes and tested in the lab under four conditions to determine the effects of installation practices, field operating conditions, and age on efficiency.

## 1.2 Background

As required by the Energy Policy and Conservation Act of 1975, the National Bureau of Standards developed test procedures to establish methods of energy consumption of certain appliances. On May 10, 1978, DOE promulgated the test procedures for furnaces and boilers. Those procedures and the amendments of August 10, 1980 provided the basis for ASHRAE Standard 103, the gas furnace and boiler efficiency test standard. ASHRAE developed the standard using the American National Standards Institute (ANSI) consensus process. It was approved by the ASHRAE Standards Committee on June 27, 1982. The original standard was ANSI/ASHRAE 103-1982 (ASHRAE 1982). ASHRAE 103-2007 will be referred to as “Standard 103” in this report.

Minimum appliance efficiency levels came into effect in the mid-1980s. When the Energy Policy and Conservation Act was amended, DOE was required to promulgate energy conservation standards for certain major appliances, including residential furnaces. In 1987, the National Appliance Energy Conservation Act established initial minimum efficiency standards for residential gas furnaces at 78% AFUE for most gas furnaces effective January 1, 1992. The minimum efficiency for furnaces was revised upward in 2007—gas furnaces produced after 2015 are required to have an AFUE of 80% or higher.

The DOE AFUE rating procedure and ASHRAE Standard 103 are not developed in tandem. In 1997, DOE published a final rule that amended the original test procedure for furnaces incorporating provisions contained in test procedure waivers granted to several manufacturers from 1985 to 1996 and adding test procedures for new product designs. In 2010, DOE published a final rule that amended the original test procedure for residential furnaces to include standby and off-mode energy use. ASHRAE re-evaluates Standard 103 on a 5-year interval and published the most recent version in 2007.

ASHRAE SPC 103 is currently reviewing Standard 103 for the next publication cycle, and DOE has issued a Request for Information seeking input on the DOE AFUE test procedure. Because the timeline for the ASHRAE and DOE standards activities are not coincident, the furnaces tested in this report under ASHRAE 103 2007 may have originally been listed according to an older DOE test procedure. The authors believe the differences in ASHRAE Standard 103 and

DOE AFUE test procedure over time are not significant and are within the 0.1% experimental error of the laboratory test setup in this report (Brand and Rose 2012).

Previous Building America research has shown that correct sizing and proper installation of heating, ventilation, and air conditioning (HVAC) systems are crucial to achieving the desired occupant comfort and efficiency levels (Burdick 2011; Brand 2012). However, while there are several directly applicable and well-known installation, sizing, and distribution design guidelines, the DOE Building American team, Partnership for Advanced Residential Retrofit (PARR), has observed that installing contractors often do not follow these guidelines, especially during an upgrade of existing equipment. It is common practice within the HVAC industry to replace existing equipment without determining if the existing duct system is properly designed and sized to match the needs of the new equipment, or to fail to adjust the new equipment to match the existing distribution system. The result is equipment installed and operating at conditions outside the manufacturer's recommended range.

This project explored the effects these adverse operating conditions have on equipment performance ratings by conducting several measurements:

- Calculated steady-state efficiency based on field reported conditions.
- Measured steady-state efficiency in the lab at the same field conditions without adjusting the furnaces.
- Measured steady-state efficiency in the lab at ASHRAE Standard 103 conditions.
- Measured, annualized efficiency (AE) in the lab under conditions reported from the field and without adjusting the furnaces.
- Measured AE in the lab under Standard 103 conditions.

AE measurements are as described in ANSI/ASHRAE 103-2007. Although Standard 103 uses AFUE as the test value, AE is used in this report to avoid confusion with the DOE rating. PARR has evaluated the performance of each furnace according to ASHRAE Standard 103 and has modified the test to simulate conditions found in the field for some furnace test cases.

### **1.3 Installation Conditions**

In retrofit situations HVAC installers regularly fail to address the existing distribution system when installing new equipment, resulting in equipment operating outside the manufacturer's specifications. Ductwork that was installed many years ago to meet the previous load and match the original equipment (generally higher delivered air temperature at lower flow rates) often cannot handle the airflow requirements of newer high efficiency units. Manufacturers address this situation in their installation instructions by providing guidelines on setting the fan speed so the furnace operates in its rise range (air temperature rise across the furnace). A second common field adjustment is to set the input rate on the furnace to match the value on the label. This is done by adjusting the gas valve pressure setting and measuring the gas flow rate by observing the meter. Some installers fail to perform these adjustments and the performance is impacted.

#### **1.4 Relevance to Building America’s Goals**

Overall, the goal of DOE’s Building America program is to reduce home energy use by 30%–50% compared to the 2009 International Energy Conservation Code for new homes and pre-retrofit energy use for existing homes. To this end, Building America conducts research to “develop market-ready energy solutions that improve efficiency of new and existing homes in each U.S. climate zone, while increasing comfort, safety, and durability.”<sup>1</sup>

This project directly aligns with Building America’s objectives, as it addresses commonly observed deficiencies in forced-air natural gas furnace installations, which likely increase energy use in many American homes. Presumably, following the furnace manufacturer’s installation instructions carefully and employing industry-approved methods for equipment sizing, duct design, and filter selection should result in the unit achieving its rated performance, while failure to do so may reduce performance, thus increasing energy use. Further, degradation of performance over time caused by drift of component settings or other factors is assumed; this project provides data to test those assumptions.

#### **1.5 HVAC SAVE Program**

The furnaces analyzed in this study were taken from homes participating in Iowa’s HVAC System Adjustment & Verified Efficiency (SAVE) program, a statewide HVAC training and certification program (Yee et al. 2013). The HVAC SAVE program was developed by the Midwest Energy Efficiency Alliance (MEEA) to train contractors in the skills necessary to determine in-place performance of functioning systems, including equipment and distribution systems. Energy Stewards International has been training HVAC professionals for many years on how contractors can use static pressures, system temperatures, and airflows to identify existing system deficiencies, allowing them to make targeted repairs or adjustments. The furnaces being analyzed in this study, which were removed from the field, help to test the hypothesis that previously installed equipment is performing in less than optimal installation conditions.

#### **1.6 Performance Degradation With Age**

In addition to studying how installed conditions affect energy use, this project examined potential degradation in equipment performance over time by conducting a second round of AE testing on each unit under conditions specified in Standard 103 and comparing these results with the original rating. Building America Simulation protocols (Hendron and Engebrecht 2010) once used a degradation factor for furnace efficiency in Building Energy Optimization software (BEopt™), although that has been discontinued. The equation below provides the calculation evaluated in this project:

---

<sup>1</sup> [www1.eere.energy.gov/buildings/residential/ba\\_research.html](http://www1.eere.energy.gov/buildings/residential/ba_research.html)

$$\text{AFUE} = (\text{Base AFUE}) \times (1-M)^{\text{age}}$$

where

Base AFUE = Typical efficiency of pre-retrofit equipment when new

M = Maintenance factor

0.005 annual professional maintenance

0.015 seldom or never maintained

age = Age of equipment in years, up to a maximum of 20 years

## **2 Objective**

The objective of this project was to examine the impact that common installation practices and age-induced equipment degradation may have on the installed performance of natural gas furnaces, as measured by steady-state efficiency and AE. Recommendations are made on methods to improve field performance.

## 3 Research Methodology

### 3.1 Research Questions

The research conducted in this project addresses the following questions:

1. What is the degradation in furnace efficiency for typical field installation compared to the rated performance?
2. How should performance ratings be modified in models (such as BEopt) to account for degradation, especially for retrofit situations?
3. How do rated and measured efficiency compare for vintage furnaces?

### 3.2 Technical Approach—Data Collection and Analysis

PARR identified 12 working furnaces of various production years installed in the field, gathered operating condition information, transported each furnace to a laboratory, and tested each furnace for steady-state efficiency and for AE as described in ASHRAE Standard 103-2007.

Standard 103 provides test methods, instrumentation tolerances, and calculation techniques to determine AE. The following basic tests were conducted:

1. Steady-state test (used for both the steady-state and AE results)
2. Cool-down test
3. Heat-up test
4. Condensate heat loss under cyclic conditions test (condensing furnaces).

In addition to the test conditions recommended in Standard 103, PARR also ran the above tests mimicking the operating conditions of each furnace, as found in the field. These conditions differ from furnace to furnace as each field installation does vary. Based on MEEA's recent experience with the HVAC SAVE, a regional contractor training and certification initiative based on National Comfort Institute principles, some common conditions seen in the field are as follows:

- High external static pressures (ESPs) caused by either undersized or restrictive distribution systems: For testing, Standard 103 recommends a minimum external static of 0.2 in. w.c. (inches of water column) depending on the furnace size; 0.7–0.9 in. w.c. is commonly observed in the field. External static was measured in the field for each furnace and used for testing.
- Oversized equipment: Standard 103 accounts for oversizing by simulating burner on and off time per cycle; testing is conducted under conditions that represent a 70% oversized unit. In this project it was not possible to test oversizing because house characteristics were not logged and utility bills are not available. In previous work done by PARR (Brand and Rose 2012), it was determined that oversizing is not a significant factor for high-efficiency furnaces.
- Equipment that is off rate: The Standard 103 recommends that burner input rate be adjusted to within 2% of the hourly Btu input rating specified by the manufacturer. The gas input to the equipment was measured in the field and then tested under the same

conditions in the laboratory during the field conditions round of testing. For testing under Standard 103 conditions, input rate was corrected.

The original test plan for this project included collecting furnaces with a range of ages and designs: 1960s–1990s, ribbon burners and in-shot burners, atmospheric and fan-assisted combustion, lower efficiency and higher efficiency. The furnaces in this study covered all the cases except the very early years. The year of manufacture of the nine furnaces tested ranges from 1987–1998, three are ribbon burners, and the rest are in-shot burners, two are atmospheric combustion systems, and two are high efficiency (condensing) furnaces. This range of ages and types is fairly representative of the installed base and is sufficient for this research.

Furnaces were sourced from the Des Moines, Iowa, metropolitan area, leveraging MEEA’s work on HVAC SAVE. Twelve furnaces were collected; only nine could be tested without significant repair. PARR chose not to test the furnaces requiring significant repair because the performance could be altered.

Before each furnace was removed from the field, several measurements were taken to determine actual operating conditions. PARR is aware that measurements taken in the field are difficult to obtain within the accuracy of that recommended by Standard 103. These measurements were not used to determine AE, but rather as a general guide for determining field steady-state conditions and field conditions for laboratory testing. Table 1 provides information that was collected in the field.

**Table 1. Data Collected in the Field**

<b>Data</b>	<b>Notes</b>
<b>Nameplate Data</b>	Units, coils, fans, etc.
<b>Temperature Rise Across the Equipment</b>	°F, radiation shielded
<b>Static Pressure</b>	Using a manometer or digital gage
<b>O<sub>2</sub> % in Flue Gases</b>	Concentration, %
<b>Airflow Rate</b>	Flow plate replacing the filter

Once the initial evaluation of the equipment was completed in the field, each furnace was shipped to the Gas Technology Institute laboratory.

Table 2 shows the major data points that were collected as part of the efficiency testing, in accordance with ASHRAE 103:

**Table 2. Data Collected in the Laboratory**

Data	Notes
Room Temperature	Average of 4 points, radiation shielded
Jacket Loss	Thermocouples in 6 × 6 in. square on furnace jacket except for blower housing (contact temperature sensor may be used)
Power to Burner and Blower	kWh
Dry CO <sub>2</sub> in Flue Gases	Concentration, ppm
Room Humidity Level	Must be less than 80% RH
Time for Several Events	Seconds
Flue Gas Temperature	In a grid pattern using beaded thermocouples
Supply and Return Temperatures	Thermocouples
Gas Consumption	Cubic feet
Weight of Condensate	Using a clean non-scaling container
Gas Heating Value	Btu/standard cubic feet
Tracer Gas Concentration	Within 2% of value

Table 3 provides measurement tolerances from Standard 103. Instruments were selected and power conditioning was applied to meet these requirements.

**Table 3. Measurement Tolerances**

Measurement	Tolerance
Temperature	2°F
Gas Pressure	0.2 in. w.c.
Air Pressure	0.01 in. w.c.
CO <sub>2</sub>	0.1%
Weight	0.5%
Volume	0.5%
Time	0.5 s/h
Tracer Gas	2%
Electricity	1%
Voltage	1%
Gas	1%
Gas Heating Value	1%

### 3.3 Measurement Methods

Laboratory steady-state and AE testing for this project has been conducted according to Standard 103. Table 4 provides a summary of the measurements required for each step.

**Table 4. Test Procedure and Measurements**

Section in Standard 103	Test Name	Description	Measurements
9.1	Steady-state test	Measure energy into the furnace from natural gas and energy lost from the vent system and condensate system	Measure CO <sub>2</sub> , flue gas temperature, condensate production, gas consumption, and jacket losses under steady-state conditions.
9.5	Cool-down test	Measure energy lost to the flue gases during the post-purge or cool-down period	Flue gas temperature and time under cool-down conditions
9.6	Heat-up test	Measure energy lost to the flue gasses during heat up with delayed blower start	Flue gas temperature and time during heat-up
9.8	Condensate heat loss under cyclic conditions	Measure thermal energy lost to condensate	Fuel input, heating value, temperature, and pressure of the gas, and weight of condensate for each cycle

### 3.4 Equipment

Table 5 provides the basic set of equipment used to perform these tests.

**Table 5. Equipment Table**

Measurement	Equipment Needed
Gas Flow Rate	Gas flow meter calibrated to be accurate within 1% of flow volume
Electricity Consumption	Watt meters with an accuracy of 1% of measured energy (not included in energy balance)
Temperatures	Bead thermocouples with an accuracy of ± 2°F
Air Pressure	Manometer or pressure gage with an accuracy of ± 0.01 in. w.c.
Power Conditioning	Voltage to be controlled within 1% of nameplate requirement on furnace
CO <sub>2</sub> Concentration	Within ± 0.1%
Time	Stopwatch or timer accurate to ± 0.5 s/h
Tracer Gas	Gas chromatograph accurate to ± 2% of measured concentration
Gas Heating Value	Gas calorimeter ± 1% in Btu/ft <sup>3</sup>

### 3.5 Analysis Methodology

The full analysis procedure is described in detail in ASHRAE Standard 103-2007. Section 11 was followed for calculating the AE based on the type of furnace under test. For noncondensing and nonmodulating furnaces, Section 11.2 describes the procedures used to calculate steady-state efficiency, heating seasonal efficiency, maximum fuel input rate, and oversizing factor, all of which will be used in step 11.2.12 to calculate the AE. The same process applies for condensing furnaces as described in Section 11.3, noncondensing modulating furnaces as described in

Section 11.4, and condensing modulating furnaces as described in Section 11.5. The two equations used to calculate AE are shown in Figure 1 for nonmodulating furnaces and Figure 2 for modulating furnaces. (AFUE in Standard 103 is referred to as AE in this report to avoid confusion.)

**11.2.12 Annual Fuel Utilization Efficiency.** The annual fuel utilization efficiency (AFUE) shall be expressed as a percent and defined as follows:

$$AFUE = \frac{5200Effy_{SS}Effy_{HS}}{5200Effy_{SS} + 2.5(1 + \alpha)(4600)Effy_{HS}(Q_P/Q_{IN})}$$

where

- 5200 = average annual heating degree-days,
- $Effy_{HS}$  = value as defined in 11.2.11,
- $Effy_{SS}$  = value as defined in 11.2.7,
- $\alpha$  = value as defined in 11.2.8.2,
- 4600 = average non-heating-season hours per year.

Figure 1. Section 11.2.12 excerpt from ASHRAE Standard 103-2007

**11.4.12 Annual Fuel Utilization Efficiency.** The annual fuel utilization efficiency, AFUE, for each  $Effy_{HS}$  shall be expressed as a percentage and defined as

$$AFUE = \frac{5200Effy_{SS,w}Effy_{HS}}{5200Effy_{SS,w} + 2.5(1 + \alpha)(4600)Effy_{HS}(Q_P/Q_{IN})}$$

where

- 5200 = annual average heating degree-days,
- $Effy_{SS,w}$  = weighted average steady-state efficiency as defined in 11.4.8.9,
- $Effy_{HS}$  = heating seasonal efficiency as defined in 11.4.11.3,
- $Q_{IN}$  = maximum fuel input rate as defined in 11.4.8.1.1,
- $\alpha$  = oversizing factor for furnaces and boilers as defined in 11.4.8.2,
- $Q_P$  = pilot flame fuel input in Btu/h,
- 4600 = average non-heating-season hours per year.

Figure 2. Section 11.4.12 excerpt from ASHRAE Standard 103-2007

### 3.6 Furnaces Tested

Twelve furnaces were collected from the field. Only nine could be tested in the lab without significant repair that would impact performance. A short description of each furnace, a photograph, nameplate information, and field measurements are included in Figure 3 through Figure 14 and Table 6 through Table 17.

### 3.6.1 InterCity Products GN100A016AIN

The GN100A016AIN model is a mid-efficiency gas furnace with an induced draft combustion system. The unit was built in April 1992 and removed from service in September 2012.



Figure 3. Furnace #1 InterCity Products

Table 6. Furnace #1 InterCity Products

Specifications			
<b>Manufacturer</b>	InterCity Products	<b>Height, in.</b>	40.125
<b>Model</b>	GNI100A016AIN	<b>Width, in.</b>	22.75
<b>Serial Number</b>	R921600151	<b>Depth, in.</b>	28.25
<b>Year</b>	April 1992	<b>Duct Depth, in.</b>	18.5
<b>Input Capacity</b>	100,000	<b>Duct Width, in.</b>	21.25
<b>Output Capacity</b>	80,400		
<b>DOE-Rated AFUE</b>	80.5		
Field Data Reported			
<b>Airflow (CFM)</b>	920	<b>Temperature Rise, °F</b>	84
<b>O<sub>2</sub> %</b>	9.6	<b>ESP, in. w.c.</b>	0.9
<b>Flue Temperature, °F</b>	467		

### 3.6.2 InterCity Products GUI100A012GIN

The GUI100A012GIN model is a mid-efficiency gas furnace with an induced draft combustion system. This unit was built in March 1991 and removed from service in September 2012.



Figure 4. Furnace #2 InterCity Products

Table 7. Furnace #2 InterCity Products

Specifications			
Manufacturer	InterCity Products	Height, in.	39.25
Model	GUI100A012GIN	Width, in.	19.25
Serial Number	L931034889	Depth, in.	28.25
Year	March 1991	Duct Depth, in.	18.5
Input Capacity	100,000	Duct Width, in.	17.75
Output Capacity	80,000		
DOE-Rated AFUE	80.1		
Field Data Reported			
Airflow (CFM)	878	Temperature Rise, °F	73
O <sub>2</sub> %	11.3	ESP, in. w.c.	0.7
Flue Temperature, °F	504		

### 3.6.3 Lennox G12QE382-10

The G12QE382-10 model is an atmospheric gas furnace using indoor combustion air, a draft diverter, and an atmospheric burner. The unit was built in June 1989 and removed from service in September 2012.



Figure 5. Furnace #3 Lennox

Table 8. Furnace #3 Lennox

Specifications			
Manufacturer	Lennox	Height, in.	49
Model	G12QE382-10	Width, in.	16.5
Serial Number	5889607663	Depth, in.	26.25
Year	June 1989	Duct Depth, in.	17.75
Input Capacity	82,000	Duct Width, in.	14.25
Output Capacity	None Found		
DOE-Rated AFUE	72.5		
Field Data Reported			
Airflow (CFM)	947	Temperature Rise, °F	88
O <sub>2</sub> %	13.2	ESP, in. w.c.	0.6
Flue Temperature, °F	548		

### 3.6.4 InterCity Products GN100A016CIN

The GN100A016CIN model is a mid-efficiency gas furnace using an induced-draft combustion system. The unit was manufactured in October 1993 and removed from service in September 2012. The front panels of this furnace were missing. New panels were fabricated for the test.



Figure 6. Furnace #4 InterCity Products

Table 9. Furnace #4 InterCity Products

Specifications			
<b>Manufacturer</b>	InterCity Products	<b>Height, in.</b>	40.625
<b>Model</b>	GN100A016CIN	<b>Width, in.</b>	23
<b>Serial Number</b>	L934418652	<b>Depth, in.</b>	28.25
<b>Year</b>	October 1993	<b>Duct Depth, in.</b>	18.25
<b>Input Capacity</b>	100,000	<b>Duct Width, in.</b>	21.25
<b>Output Capacity</b>	80,400		
<b>DOE-Rated AFUE</b>	80.5		
Field Data Reported			
<b>Airflow (CFM)</b>	792	<b>Temperature Rise, °F</b>	84
<b>O<sub>2</sub> %</b>	9.6	<b>ESP, in. w.c.</b>	0.9
<b>Flue Temperature, °F</b>	467		

### 3.6.5 Fraser Johnston PBKM-L016N080A

The PBKM-L016N080A model is a mid-efficiency furnace using an induced draft combustion system. This furnace was received without a front panel, so one was fabricated. The unit was built in February 1994 and removed from service in September 2012.



Figure 7. Furnace #5 Fraser Johnston

Table 10. Furnace #5 Fraser-Johnston

Specifications			
Manufacturer	Fraser-Johnston	Height, in.	40.25
Model	PBKM-L016N080A	Width, in.	22.25
Serial Number	EBCM101513	Depth, in.	28.25
Year	February 1994	Duct Depth, in.	19.5
Input Capacity	80,000	Duct Width, in.	21.125
Output Capacity	64,000		
DOE-Rated AFUE	80		
Field Data Reported			
Airflow (CFM)	619	Temperature Rise, °F	86
O <sub>2</sub> %	10.8	ESP, in. w.c.	0.9
Flue Temperature, °F	511		

### 3.6.6 Lennox G23Q4/5-100-4

The G23Q4/5-100-4 model is a mid-efficiency furnace using an induced draft combustion system. The unit was built in January 1998 and removed from service in September 2012.



Figure 8. Furnace #6 Lennox

Table 11. Furnace #6 Lennox

Specifications			
Manufacturer	Lennox	Height, in.	46.25
Model	G23Q4/5-100-4	Width, in.	22.25
Serial Number	5898A 35920	Depth, in.	28.5
Year	January 1998	Duct Depth, in.	18.75
Input Capacity	100,000	Duct Width, in.	19
Output Capacity	80,000		
DOE-Rated AFUE	80		
Field Data Reported			
Airflow (CFM)	841	Temperature Rise, °F	89
O <sub>2</sub> %	13.3	ESP, in. w.c.	0.8
Flue Temperature, °F	562		

### 3.6.7 Amana GUC090X50B

The GUC090X50B model is a high-efficiency direct vent condensing gas furnace. The front panels for this furnace were missing and new panels were fabricated. The unit was built in September 1996 and removed from service in September 2012.



Figure 9. Furnace #7 Amana

Table 12. Furnace #7 Amana

Specifications			
Manufacturer	Amana	Height, in.	48
Model	GUC090X50B	Width, in.	24.625
Serial Number	9609152460	Depth, in.	28
Year	September 1996	Duct Depth, in.	19.75
Input Capacity	90,000	Duct Width, in.	23.125
Output Capacity	85,000		
DOE-Rated AFUE	94.4		
Field Data Reported			
Airflow (CFM)	1071	Temperature Rise, °F	53
O <sub>2</sub> %	12.9	ESP, in. w.c.	0.8
Flue Temperature, °F	144		

### 3.6.8 Rheem RGOA100CER

The RGOA100CER model is an atmospheric gas furnace with a draft diverter. This furnace could not be tested because it was damaged beyond repair during shipping. The unit was built in August 1991 and removed from service in September 2012.



Figure 10. Furnace #8 Rheem

Table 13. Furnace #8 Rheem

Specifications			
<b>Manufacturer</b>	Rheem	<b>Height, in.</b>	46.25
<b>Model</b>	RGOA100CER	<b>Width, in.</b>	17.5
<b>Serial Number</b>	MN3D104 F3491 0205	<b>Depth, in.</b>	28.125
<b>Year</b>	August 1991	<b>Duct Depth, in.</b>	20
<b>Input Capacity</b>	100,000	<b>Duct Width, in.</b>	16
<b>Output Capacity</b>	65,000		
<b>DOE-Rated AFUE</b>	65		
Field Data Reported			
<b>Airflow (CFM)</b>	997	<b>Temperature Rise, °F</b>	84
<b>O<sub>2</sub>%</b>	10	<b>ESP, in. w.c.</b>	0.8
<b>Flue Temperature, °F</b>	497		

### 3.6.9 Armstrong GUK075D14-18

The GUK075D14-18 model is a direct-vent high-efficiency condensing gas furnace. It was manufactured in September 1994 and removed from service in September 2012.



Figure 11. Furnace #9 Armstrong

Table 14. Furnace #9 Armstrong

Specifications			
Manufacturer	Armstrong	Height, in.	46
Model	GUK075D14-18	Width, in.	22
Serial Number	8494J33762	Depth, in.	28
Year	September 1994	Duct Depth, in.	19.5
Input Capacity	75,000	Duct Width, in.	20.75
Output Capacity	67,000		
DOE-Rated AFUE	90		
Field Data Reported			
Airflow (CFM)	693	Temperature Rise, °F	86
O <sub>2</sub> %	12.2	ESP, in. w.c.	0.9
Flue Temperature, °F	555*		

\*Reported value

### 3.6.10 Trane TUS060A936AO

The TUS060A936AO model is an atmospheric gas furnace with a draft diverter. Front panels were fabricated to replace those lost in shipment. The center heat exchanger mounting screw was replaced. The unit was manufactured in September 1987 and removed from service in September 2012.



Figure 12. Furnace #10 Trane

Table 15. Furnace #10 Trane

Specifications			
Manufacturer	Trane	Height, in.	49
Model	TUS060A936AO	Width, in.	18.125
Serial Number	B36599305	Depth, in.	28.125
Year	September 1987	Duct Depth, in.	20
Input Capacity	60,000	Duct Width, in.	17
Output Capacity	None Found		
DOE-Rated AFUE	68.4		
Field Data Reported			
Airflow (CFM)	604	Temperature Rise, °F	87
O <sub>2</sub> %	11.3	ESP, in. w.c.	0.8
Flue Temperature, °F	497		

### 3.6.11 Lennox G16Q3757

The G16Q3757 model is a mid-efficiency gas furnace using an induced draft combustion system. This was damaged beyond repair during shipping and could not be tested. It was manufactured in March 1989 and removed from service in September 2012.



Figure 13. Furnace #11 Lennox

Table 16. Furnace #11 Lennox

Specifications			
Manufacturer	Lennox	Height, in.	49
Model	G16Q3757	Width, in.	16.25
Serial Number	5889C07272	Depth, in.	26.25
Year	March 1989	Duct Depth, in.	18
Input Capacity	75,000	Duct Width, in.	14
Output Capacity	None Found		
DOE-Rated AFUE	78.5		
Field Data Reported			
Airflow (CFM)	720	Temperature Rise, °F	76
O <sub>2</sub> %	13.2	ESP, in. w.c.	0.8
Flue Temperature, °F	531		

### 3.6.12 Lennox GH6D 100M

The GH6D 100M model is an atmospheric gas furnace that uses a draft diverter. This furnace could not be tested because the height exceeded the test chamber capability. The unit was manufactured in May 1963 and removed from service in September 2012.



Figure 14. Furnace #12 Lennox

Table 17. Furnace #12 Lennox

Specifications			
Manufacturer	Lennox	Height, in.	60.75
Model	GH6D 100M	Width, in.	21
Serial Number	None Found	Depth, in.	27.5
Year	May 1963	Duct Depth, in.	17
Input Capacity	100,000	Duct Width, in.	19
Output Capacity	80,000		
DOE-Rated AFUE	N/A		
Field Data Reported			
Airflow (CFM)	861	Temperature Rise, °F	88
O <sub>2</sub> %	11.5	ESP, in. w.c.	0.8
Flue Temperature, °F	485		

## 4 Analysis

Gas furnace efficiency was determined using five different metrics to compare laboratory and field performance. Table 18 below shows the efficiency metrics.

**Table 18. Efficiency Measurements**

Efficiency Metric	Description
SSE FC Calc	Steady-state efficiency under field conditions calculated from field data
SSE FC LM	Steady-state efficiency under field conditions as measured in the lab
SSE SC LM	Steady-state efficiency under ASHRAE Standard 103 test conditions measured in the lab; airflow and input rate adjusted
AE FC LM	AE using ASHRAE Standard 103 under field conditions measured in the lab
AE SC LM	AE using ASHRAE Standard 103 test conditions measured in the lab; airflow and input rate adjusted to Standard 103 conditions

### 4.1 Steady-State Efficiency

Steady-state efficiency was measured under constant load conditions in the field and in the lab (thermostat calling for heat). Field data were reported by the HVAC contractor. Lab testing included the Gas Technology Institute rack-mounted combustion analyzer system that is calibrated daily and the instruments used in the Standard 103 test procedure as discussed earlier in this report. Field conditions are based on handheld combustion analyzers, digital static pressure transducers for ESP, and a flow plate for airflow rate.

Table 19 shows the data collected in the field and the manufacturer-recommended temperature rise. Note that in almost every case, the furnaces were operating in the field above the manufacturer’s temperature rise recommendation.

**Table 19. Furnace Field Data and Steady-State Efficiency**

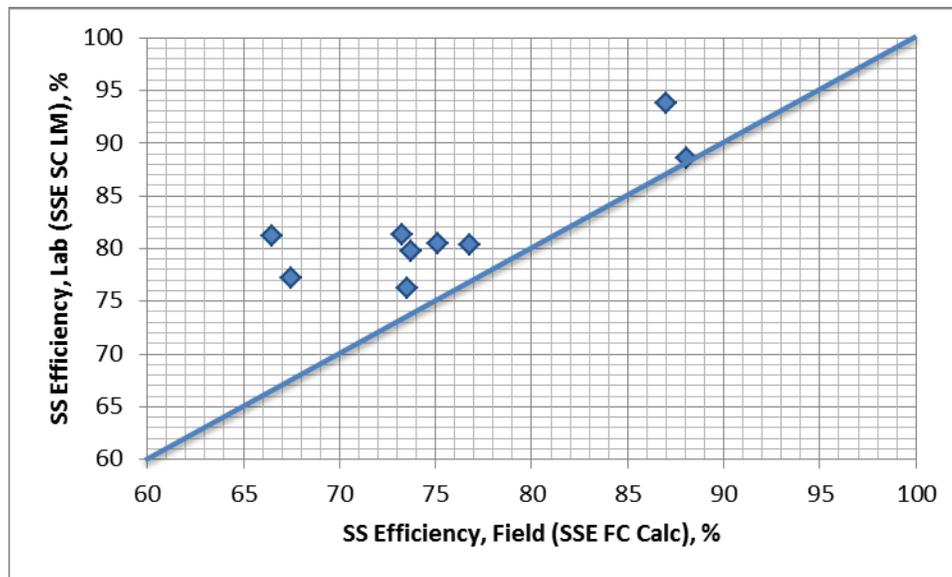
Number	Manufacturer	O2 (%)	ESP (in. w.c.)	Airflow Rate (CFM)	Flue Temperature (°F)	Temperature Rise (°F)	Manufacturer Temperature Rise Range (°F)
1	ICP	9.6	0.9	920	467	84	30–60
2	ICP	11.3	0.7	878	504	73	40–70
3	Lennox	13.2	0.6	947	548	88	70–100
4	ICP	12	0.9	792	433	90	30–60
5	Fraser-Johnston	10.8	0.9	619	511	86	20–50
6	Lennox	13.3	0.8	841	562	89	30–60
7	Amana	12.9	0.8	1071	144	53	35–65
9	Armstrong	12.2	0.9	693	555	86	50–80
10	Trane	11.3	0.8	604	497	87	40–70

Because AFUE and AE cannot be measured in the field, steady state efficiency is used as a field efficiency indicator. A comparison was made with the calculated steady-state efficiency value from field data and steady-state efficiency under the Standard 103 conditions as measured in the lab, SSE SC LM. Table 20 shows the steady-state efficiency calculated from the field data and SSE SC LM measured in the lab under Standard 103 test conditions of 0.2 in. w.c. ESP. In all cases, the field value is less than the laboratory-measured value.

**Table 20. Steady-State Efficiency Comparison**

Number	Manufacturer	SSE FC Calc	SSE SC LM
1	ICP	76.8	80.4
2	ICP	73.3	81.4
3	Lennox	67.5	77.2
4	ICP	75.1	80.5
5	Fraser Johnston	73.7	79.7
6	Lennox	66.5	81.2
7	Amana	87.0	93.7
9	Armstrong	88.1	88.6
10	Trane	73.5	76.3

Figure 15 compares the steady-state efficiency between the field and Standard 103 conditions. The 45-degree line represents perfect agreement, above the line means the lab measured value is greater, or conversely that the calculated value from field measurement is lower. The difference between the means is 6.4%. A paired t-test of the null hypothesis that the sample means are not different from each other at  $p < 0.05$  is rejected based on a statistical analysis. The means are significantly different for these two data sets, indicating poor performance in the field caused by poor installation practices or misadjustment.



**Figure 15. Steady-state efficiency field and Standard 103 lab conditions**

Field installation parameters were evaluated to determine the root cause for this difference. The airflow rate measured in the field and in Standard 103 steady-state efficiency measurement (not the same static pressure) is provided in Table 21. Note that the Standard 103 numbers are significantly higher than in the field because of improper air distribution system design.

**Table 21. Airflow in the Field and Standard 103 Conditions**

Number	Manufacturer	Field Airflow (CFM)	Standard 103 Conditions Airflow (CFM)
1	ICP	920	1925
2	ICP	878	1635
3	Lennox	947	943
4	ICP	792	1754
5	Fraser Johnston	619	1488
6	Lennox	841	1664
7	Amana	1071	1516
9	Armstrong	693	1389
10	Trane	604	945

An indirect measure of how well the field airflow is adjusted is to measure the temperature rise across the furnace and identify where it lies in the manufacturer’s recommended “rise range” as follows: The midpoint value is the target; higher values result in decreased efficiency and lower values increase the risk of corrosion in the heat exchanger. Table 22 shows the rise values from the field and Standard 103 test along with the manufacturers’ recommendations. Note that fan speed adjustments are very coarse and meeting the requirement is not always possible.

**Table 22. Furnace Rise Range**

Number	Manufacturer	Manufacturer Temperature Rise Range (°F)	Field Temperature Rise (°F)	Standard 103 Temperature Rise (°F)
1	ICP	30–60	84	43
2	ICP	40–70	73	49
3	Lennox	70–100	88	69
4	ICP	30–60	90	47
5	Fraser-Johnston	20–50	86	45
6	Lennox	30–60	89	52
7	Amana	35–65	53	66
9	Armstrong	50–80	86	58
10	Trane	40–70	87	51

Airflow was not set within the rise range for many of these furnaces in the field, or the ductwork was too small to achieve the required airflow. Note that most field furnaces were operating at the top or above the rise range, resulting in lower steady-state efficiency.

As a final note on field adjustments, input rate adjustments were not required for laboratory testing of the furnaces except for furnace #10. This furnace was received set at 76,000 Btu/h compared to the 60,000 Btu/h on the label. There was no individual test to determine the efficiency change associated with adjusting the input in isolation, but adjusting both the input rate and airflow improved the steady-state efficiency by 2.8% for this furnace.

PARR attempted to measure the steady-state efficiency of the furnaces under field airflow and static pressure conditions (SSE FC LM) to determine if the field conditions could be replicated in the lab. Table 23 shows the field-measured airflow rate and the lab-measured airflow rate when the furnaces were installed to the same reported ESP conditions needed to replicate the ductwork pressure drop from the field. There is a significant discrepancy between these two values, for reasons unknown to the investigator. It is likely that either the reported field ESP or field airflow measurements are not reliable. Potential causes are that the flow plate replaced a dirty filter or that the return duct geometry was not suitable for use with the flow plate.

**Table 23. Airflow Rate Differences in the Field and Lab at the Same Static Pressure**

<b>Furnace</b>	<b>Field-Measured Airflow Rate (CFM)</b>	<b>Lab-Measured Airflow Rate (CFM)</b>
<b>1</b>	920	1,288
<b>2</b>	878	1,206
<b>3</b>	947	661
<b>4</b>	792	1,048
<b>5</b>	619	938
<b>6</b>	841	1,407
<b>7</b>	1,071	1,516
<b>9</b>	693	955
<b>10</b>	604	665

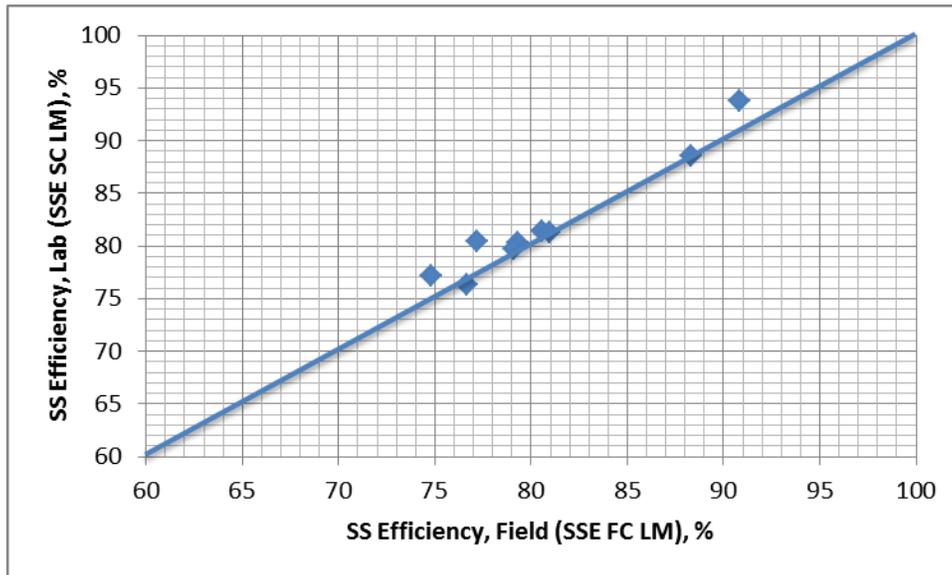
PARR elected to set up the furnaces in the lab according to the static pressure reading rather than the airflow reading, because it was considered to be the more accurate of the two field measurements. SSE FC LM was compared to the steady-state efficiency under the conditions in Standard 103 (SSE SC LM). Recall that that the Standard 103 condition test is done after airflow adjustments are made and the input rate is adjusted.

Table 24 shows the differences between the two values.

**Table 24. Steady-State Efficiency Measured in the Lab**

Furnace	Field Conditions Lab-Measured Steady-State Efficiency (SSE FC LM), %	Standard 103 Conditions Lab-Measured Steady-State Efficiency (SSE SC LM), %
1	79.3	80.4
2	80.6	81.4
3	74.8	77.2
4	77.2	80.5
5	79.1	79.7
6	80.9	81.2
7	90.9	93.7
9	88.3	88.6
10	76.7	76.3

Figure 16 shows the two efficiency values on a chart; the 45-degree line represents perfect agreement.



**Figure 16. Steady-state efficiency field and Standard 103 lab conditions**

The test results show that there is still a statistically significant difference between the two means, but it is only on the order of 1.2% because replicating the field environment in the lab is difficult.

**4.2 Annual Fuel Utilization Efficiency and Annualized Efficiency**

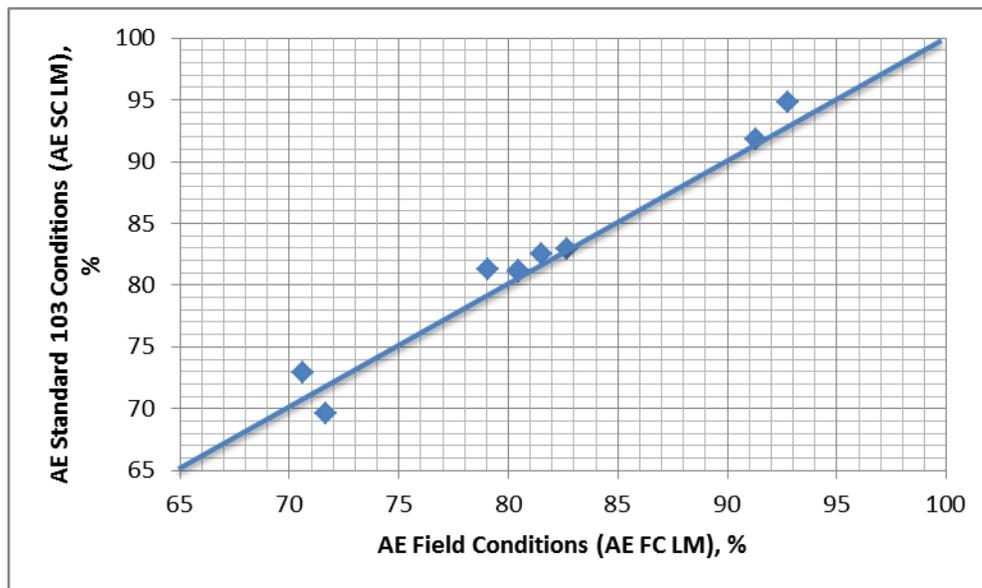
AFUE is the DOE efficiency rating point as measured under specific conditions in the lab. In this report, AE is used for the Standard 103 rating point. When tested according to Standard 103

without change, Annualized Efficiency Standard Conditions Lab Measured (AE SC LM) is used. When Standard 103 is modified to reflect field conditions, Annualized Efficiency Field Conditions Lab Measured (AE FC LM) is used. Table 25 provides the test results.

**Table 25. AE Under Field and Standard 103 Conditions**

Furnace	AE Field Conditions (AE FC LM), %	AE Standard 103 Conditions (AE SC LM), %
1	80.47	81.04
2	82.7	82.9
3	70.6	73.0
4	79.1	81.3
5	80.5	81.1
6	81.5	82.5
7	92.7	94.9
9	91.3	91.8
10	71.7	69.6

Figure 17 shows the data in graphical form where the 45-degree line indicates perfect agreement.



**Figure 17. AE field and Standard 103 lab conditions**

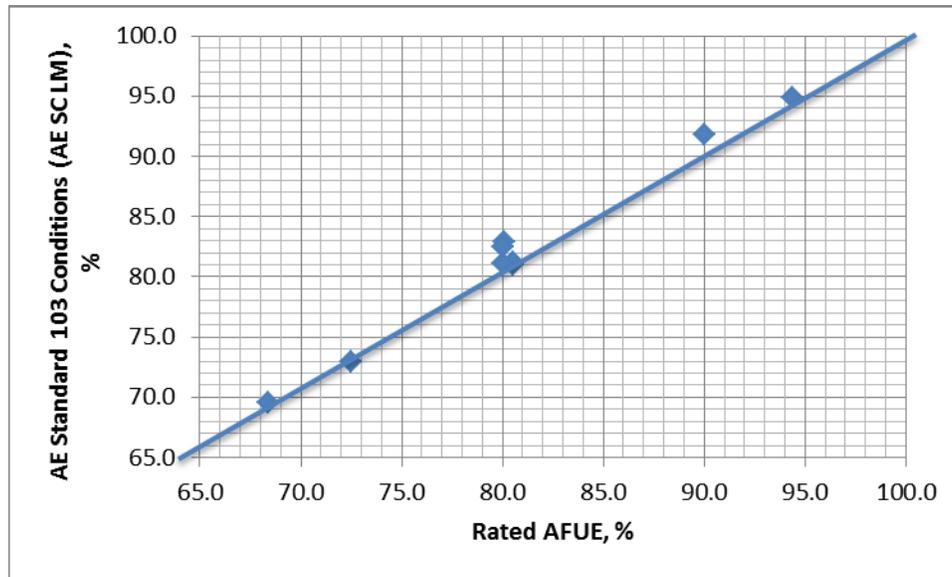
Using the same paired t-test for significance with this data set, the mean difference of 0.8% is not significant when testing AE under field and AE under Standard 103 conditions in the lab. The difficulty associated with setting up field conditions in the lab, as mentioned in the steady-state efficiency analysis, coupled with the four heat-up, cool-down, and condensate collection parts of the test masks the differences.

Table 26 shows the difference between the rated AFUE on the furnace and the lab-measured value under Standard 103 conditions (AE SC LM). This test does not rely on replicating the field conditions in the lab. A comparison is made between these values, though the individual furnaces were not rated for AFUE when they were new and the test procedures are not identical.

**Table 26. Rated AFUE and AE Under Standard 103 Conditions**

Furnace	Rated AFUE (%)	AE Standard Conditions (AE SC LM), %
1	80.5	81.0
2	80.1	82.9
3	72.5	73.0
4	80.5	81.3
5	80.0	81.1
6	80.0	82.5
7	94.4	94.9
9	90.0	91.8
10	68.4	69.6

Figure 18 shows the data in graphical form.



**Figure 18. Rated AFUE compared to AE Standard 103 lab conditions**

Using the same hypothesis testing, there is a significant difference between the rated AFUE and the lab-measured AE from Standard 103 for this data set, at 1.3%. There are several potential reasons for the slight difference, including differences in the test procedures, changes to the standards over time, sampling differences, bias in the test, or emissivity changes from oxidation of the heat exchangers. Standard 103 is revised every 4 years and the DOE standard also

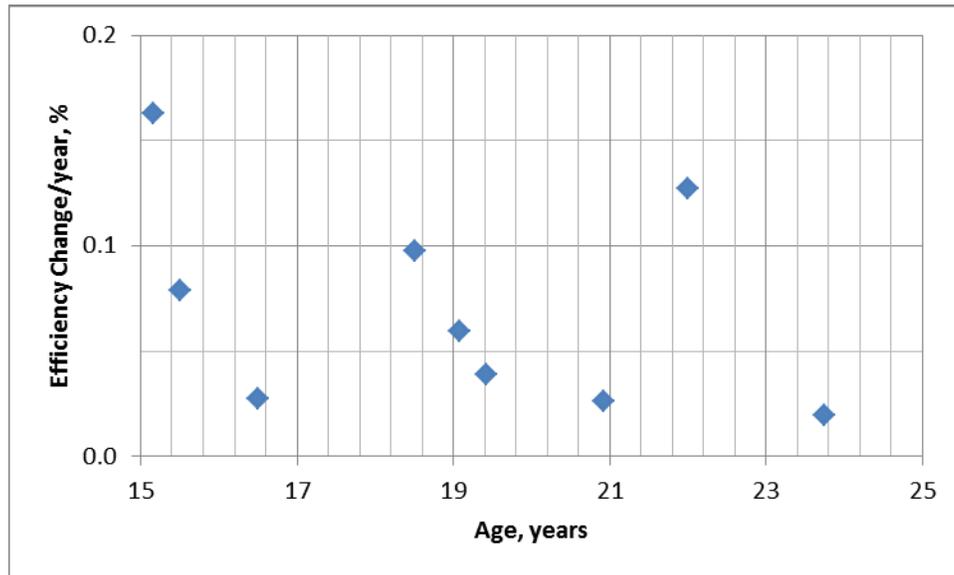
undergoes periodic revision, so it is possible that the DOE rating test procedure was significantly different than the 2007 Standard.

The hypothesis that there is a time dependence to furnace efficiency is tested in Section 4.3.

### 4.3 Efficiency Change With Time

The efficiency measurements for the furnaces collected from the field provide a unique opportunity to evaluate changes to the efficiency of furnaces with time.

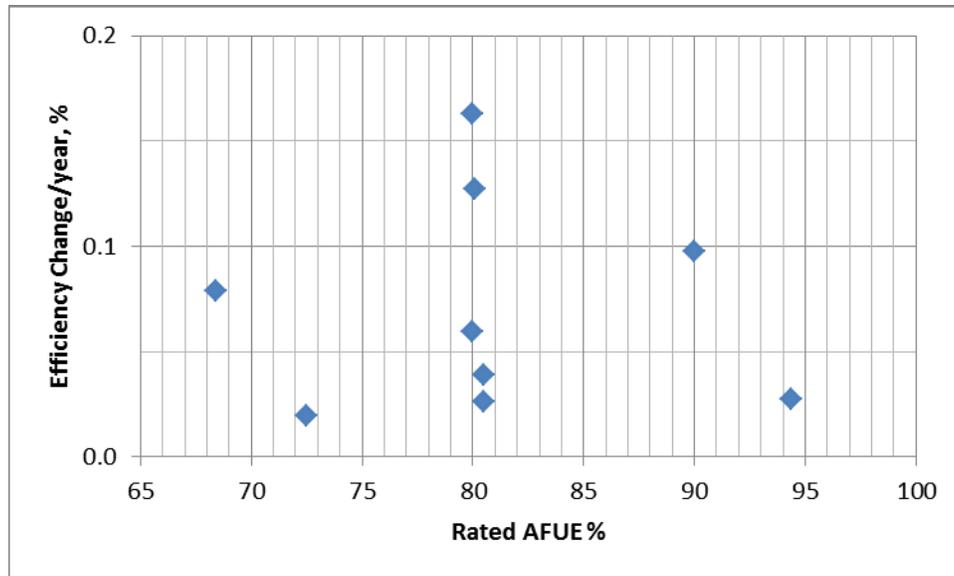
Figure 19 plots the age of the furnace versus percent change per year of furnace efficiency as measured by the difference from rated AFUE and AE measured in the lab (AE SC LM), which is independent of field measurement.



**Figure 19. Efficiency change versus age**

A linear fit of the data did not result in a slope or intercept value that was statistically significant. The implications are that there is no time dependency in this metric. It is also possible that there is some bias in the AE test compared to the rated DOE value, as mentioned earlier. At minimum, the authors contend that these data can be used to conclude that there is no time dependency to the AE measurement when using rated AFUE as a baseline; thus, the degradation predicted by Equation 1 is not supported in this research.

A final comparison was made between efficiency change, as calculated by rated AFUE-AE SC LM, versus age to determine if there was a relationship between the two. The graph is provided in Figure 20.



**Figure 20. Rated AFUE versus efficiency change per year**

This analysis shows that there is no relationship between rated AFUE and a linear efficiency change per year.

## 5 Results and Discussion

The primary objective of this project was to determine how age and adverse installation conditions affect natural gas field performance as measured by AE. The results from this study are summarized below:

1. There is a significant difference between the steady-state efficiency calculated from field data and the steady-state efficiency measured in the lab under Standard 103 conditions. The difference in the mean is 6.4%. An analysis of the nine data points in Figure 16 using a paired student t-test and  $p < 0.05$  for significance indicates that the two data sets are significantly different. The implication is that field performance is 6.4% lower than rated conditions for this sample because of poor installation practices or misadjustment.
2. There is a significant difference between steady-state efficiency measured in the lab under field conditions and Standard 103 conditions, at 1.2%. Replicating the field environment proved to be difficult in this test. Because the furnaces were removed from their installation sites, additional field data could not be collected.
3. There is no significant difference between AE under field conditions and AE under Standard 103 conditions measured in the lab. The difficulty associated with setting up field conditions in the lab, as mentioned above, coupled with the four heat-up, cool-down, and condensate collection parts of the test may mask the difference.
4. The mean lab-measured AE from the Standard 103 is 1.3% higher than rated AFUE, a statistically significant difference. This test does not rely on replicating field conditions in the lab. There are several potential reasons for this finding, including differences in the test procedures, changes to the standards over time, sampling differences, bias in the test, or emissivity changes from oxidation of the heat exchangers. Standard 103 is revised every 4 years and the DOE standard also undergoes periodic revision, so it is possible that the older equipment was measured under a procedure no longer included in the Standard 103.
5. Testing a linear fit of efficiency with time was not significant for either the slope or intercept values. The implications are that there is a nonzero increase in rated AFUE, but it is not time dependent, indicating that the change happens in the first 15 years of field use. It is also possible that there is some bias in the lab test compared to the DOE standard, as mentioned earlier. The authors conclude that the degradation predicted by Equation 1 is not supported in this research.

The research questions are addressed below:

Q1: What is the degradation in furnace efficiency for typical field installation compared to the rated performance?

A1: Furnace steady-state efficiency calculated from field data is 6.4% below that measured in the laboratory under Standard 103 conditions, a statistically significant difference.

Q2: How should efficiency values be modified in models (such as BEopt) to account for degradation, especially for retrofit situations?

A2: BEopt and other models do not need to adjust for differences between rating conditions and the field environment for furnaces that are installed properly.

Q3: How do rated and measured efficiency compare for vintage furnaces?

A3: Older furnaces show no degradation of performance over an average lifetime of 19 years. From the data, time is not a significant variable in the regression, so there may be an initial increase or a slight bias caused by differences in test standards.

## 6 Conclusions and Recommendations

The conclusions of this research are that the rated DOE AFUE is a good measure of the performance of natural gas furnaces in the field where the installation instructions are followed. Field conditions are difficult to replicate in the laboratory, so lab testing that replicates the field environment requires more study. Efficiency comparisons between the rated value and the Standard 103 test in the lab show no degradation after an average lifetime of 19 years, in fact a slight increase was measured. Using this comparison, the efficiency levels do not show a significant time dependency.

PARR recommends that BEopt and other models continue to use the DOE-rated AFUE without adjustment for installation practices or degradation with time. This data set supports those recommendations. Field measurements of efficiency, static pressure, and airflow (using a flow plate) were inconsistent in this study when compared to laboratory measurements. It is recommended that field measurements be used only as a general indicator of performance when tuning a furnace or adjusting airflow, not as an absolute indication of performance for modeling or energy savings analysis.

PARR conducted this investigation to determine which deficiencies in the field, if any, hold the largest energy saving potential. Setting the furnace on rate, and tuning the fan to the manufacturer's recommended rise range (temperature rise across the furnace) are the two most significant factors in achieving good performance, as recommended by the manufacturer. If the fan speed cannot be adjusted properly, changes to the distribution system need to be made. A qualified installer should follow the manufacturer's installation instructions regarding these and other settings to get the best performance.

Future natural gas furnace testing is recommended to add data to the cases where a relationship could not be determined in this project: replicating field conditions in the lab and establishing efficiency change with time. For example, a test where furnaces are rated, installed in the field for normal operation, and then re-rated by the rating agency using the same DOE test procedure to determine if there is a significant degradation in the rating point. It may also be valuable to determine if a poorly installed furnace would operate significantly below the rating point. Examples would be furnaces working outside the rise range (very high or very low), and furnaces cycling off the high limit controller for a significant part of the time. Finally, simulation models have improved significantly since rated AFUE was first used as an indicator of performance. Research is recommended to identify several performance metrics that can be used by simulations to improve the agreement between calculated and actual field performance.

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