Investigation of High Efficiency Furnace SSE Measurements versus AFUE

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The SSE vs. AFUE Comparison Study Report summarizes the results of an investigation into the measured steady-state efficiency (SSE) of replacement gas furnaces under the Wisconsin weatherization program. The investigation came about because a number of cases have been documented in which tested SSE fell more than 2 percentage points below the rated annual fuel utilization efficiency (AFUE) of a replacement condensing furnace. These cases raise issues as to whether some furnace models do not achieve their rated efficiency in the field, or whether there is an issue with how the SSE testing is conducted under the program.

Our investigation involved re-testing nine furnaces under more rigorous conditions involving multiple combustion analyzers and additional data collection (five of these units had previously failed a QC check for SSE within 2 percentage points of AFUE). We also contacted the manufacturers of several combustion analyzers, as well as one well-known independent expert in the field of space-heating combustion analysis.

Key findings from our investigation are as follows:

1. One line of combustion analyzers used in the Wisconsin program (Testo) does not incorporate the heat recovered by condensing water vapor from combustion products in its north american SSE algorithms. At flue gas temperatures below about 120 ^{o}F, this line of instruments will indicate a significantly lower SSE than other makes of combustion analyzers, and may show an SSE that is well below AFUE (which does incorporate latent heat recovery).

2. For analyzers that *do* attempt to account for latent heat recovery from condensation of flue gas water vapor (Bacharach and TPI), there are important differences between field SSE tests and the AFUE test procedure. SSE measurements are based on estimated latent heat recovery from measured flue gas temperature in relation to the dew point of the fuel used by the furnace under steady-state operating conditions. AFUE ratings on the other hand are based on a more accurate protocol entailing collecting and measuring the actual amount of condensate removed from the combustion products. Some furnaces condense more water vapor than is indicated by their aggregate flue gas characteristics would indicate. Moreover, AFUE measurements are made under cycling operation, which probably yields higher latent recovery (because the secondary heat exchanger is colder on average) than steady-state operation. We are not able to explicitly quantify how these differences affect comparisons of field SSE measurements and AFUE ratings, but latent recovery for a typical condensing furnace is likely to add 4 to 6 percentage points to its combustion efficiency: a 30 to 50 percent difference in estimated latent recovery between field SSE and rated AFUE would translate into about a two percentage point difference in overall efficiency between the two methods, and SSE-based estimates are likely to be lower than AFUE ratings.

3. The temperature of incoming combustion air affects the measured efficiency: measured SSE will be slightly lower in cold weather and slightly higher in warm weather. AFUE ratings for sealed-combustion furnaces that use outdoor air are based on a national average outdoor temperature of 42^{o}F. A furnace will test about 1 to 1.5 percentage points below AFUE on a cold winter day based solely on the difference in intake air temperature

(and a furnace tested on a hot summer day will similarly test about 1 to 1.5 percentage points above AFUE).[1]

4. The intake air temperature situation is further complicated by the fact that not all combustion analyzers can separately monitor intake air temperature for sealed-combustion furnaces. Higher-end combustion analyzers can accept a separate thermocouple that can be inserted in the intake air pipe close to the furnace cabinet, which will yield the most accurate SSE measurements. Other models use the temperature of the main test probe during start-up as the intake air temperature: starting the unit in the basement or outdoors will lead to errors in SSE to the extent that these temperatures differ from the actual intake air temperature. Perversely, this may yield an SSE reading that is actually more comparable to AFUE if the temperature at start-up is closer to the 42^{o}F national average used in the AFUE calculations than the actual intake air temperature.[2]

5. Inherent inaccuracy in the combustion analyzer's sensors may be an issue for condensing operation. Listed thermocouple accuracy for analyzers for which we found published data ranged from ± 0.9 F^{o} to ± 4 F^{o}, and oxygen sensor accuracy was stated to be in the range of 0.2 to 0.3 percentage points. The upper end of these ranges translate into about 1.5 percentage points of uncertainty in indicated SSE under condensing conditions, owing mainly to how the uncertainty in measured stack temperature contributes to estimated latent heat recovery.

6. Field SSE measurements varied significantly over the duration of the testing. Some units started with high indicated SSE's which subsequently decreased, while others did the opposite. SSE readings from the instruments became relatively stable after about 10 minutes of operation, but tests made prior to this time are likely to be inaccurate indicators of actual steady-state operation.

7. Of the five units in this study that had previously failed a prior QC SSE test, three tested well within two percentage points of AFUE (some were above AFUE) when re-tested by use with multiple analyzers, and the remaining two units were either at or just below AFUE minus 2 depending on the analyzer. This demonstrates that how and when SSE measurements are made as well as variation in individual analyzers can have a significant impact on measured SSE. (Note also that one unit tested for this project that had not had a prior QC test measured more than 4 percentage points below AFUE).

Overall, these findings suggest that it is somewhat unrealistic to expect a properly installed and functioning furnace to always test within 2 percentage points of its AFUE rating. An improved procedure for qualifying replacement furnaces might be as follows:

[1] For typical condensing furnace test conditions, there is about a one percentage point change in SSE for each 30 F^{o} change in intake air temperature.
[2] Followed to its logical conclusion, this would suggest always starting the combustion analyzer in the client's refrigerator to get an SSE reading that is as comparable as possible to the AFUE rating!

1. Start the combustion analyzer after operating the furnace for five minutes with the probe inserted through a hole into the combustion intake pipe near the furnace cabinet. Record the intake air temperature at this time.

2. After the instrument start-up sequence is completed, switch the probe to a hole in the exhaust pipe near the furnace cabinet. If the analyzer has a separate thermocouple for intake air temperature, insert it in the hole in the intake air pipe.

3. Take SSE readings after 10 an additional minutes of furnace operation.

4. If the intake air temperature used by the analyzer is outside the range of 25^{o}F to 55^{o}F, adjust SSE according to the following formula

$$SSE_{adjusted} = SSE_{indicated} + (40 - T_{intake})/30.$$

5. If adjusted SSE is less than AFUE – 2 percentage points, check for
    a. Exhaust temperature < 130 ^{o}F
    b. CO < 100 ppm
    c. Temperature rise and gas pressures within manufacturer's specifications
    d. Presence of condensate in drain line.

6. If any of the criteria in (3) are not met, fail the unit.

The remainder of this report provides more details about what we found.

Inherent differences between SSE and AFUE

By definition, SSE and AFUE are different quantities: the former is a measure of combustion efficiency while furnace operates continuously under steady-state conditions, while the latter seeks to incorporate the effects of furnace cycling under part-load conditions. Also, in the context of this investigation, it is important to note that SSE measurements are made under as-found field conditions, while AFUE is established under defined and controlled operating conditions.

The test procedures and calculations for producing AFUE ratings for furnaces are documented under ASHRAE Standard 103-1993, "Method of Testing for Annual Fuel Utilization Efficiency of Residential Central Furnaces and Boilers." A close read of this standard suggests several notable ways in which field SSE and rated AFUE differ in the context of sealed-combustion, condensing furnaces:

- intake air temperature
- latent heat recovery
- heat-up and cool-down losses

Intake air temperature

SSE tests are conducted under uncontrolled conditions, with intake air temperatures that can range from sub-zero to 90^{o}F or more. AFUE on the other hand is based on a national average outdoor temperature of 42^{o}F.[3] The equations for sensible heat loss suggest that 1 percentage point of overall efficiency is lost for each 30 F^{o} drop in intake air temperature, so testing a furnace in very cold weather will yield an SSE that is perhaps 1.0 to 1.5 percentage points below the 42^{o}F AFUE test standard, while testing on a hot summer day will increase the indicated SSE by about the same amount.

Additionally, how and where intake air temperature is measured may be a concern. Because sealed-combustion furnaces use outdoor air for combustion, the intake air temperature can be significantly different from the ambient temperature of the basement. And because combustion air is typically drawn through 10 to 15 feet of PVC piping before it reaches the combustion chamber, it may be warmed (or cooled) somewhat before it reaches the combustion chamber, and thus may differ from the outdoor temperature as well. (Data from the nine sites we tested showed 2 to 20 F^{o} of warming between the outdoor intake and the furnace cabinet, with an average of about 7.5 F$^{o.}$)

The most accurate measurements of SSE will thus be obtained by measuring intake temperature at the point it enters the furnace. Some combustion analyzers can accept a separate thermocouple to monitor intake air temperature through a hole drilled in the air intake piping. Other models obtain an estimate of intake air temperature from the flue probe thermocouple during start-up: starting these instruments in the basement or outdoors—or starting the instrument too soon after moving it from a warmer or colder environment can lead to errors in

[3] Furnaces are actually tested with conditioned indoor air, but calculated sensible losses are adjusted to the national average outdoor temperature for units designed to operate with outside combustion air.

SSE due to an incorrect intake air temperature.[4] Ironically, these temperature errors might actually yield an estimate of SSE that is better for the purposes of comparing with rated AFUE than a more accurate measurement of actual SSE made using an actual intake air temperature that is significantly warmer or colder than the 42 ^{o}F national average used by the AFUE calculations.

Latent heat recovery

Considerable water vapor is created in the combustion process, and it is the ability to recover some of the latent heat in this water vapor that boosts the efficiency of condensing furnaces above about 90 percent.[5] Bacharach and TPI portable combustion analyzers account for latent heat recovery by analyzing the measured flue gas temperature in relation to the dew point of the combustion products (which varies based on the fuel in question and the amount of excess air).[6] The details of the algorithms used by the analyzers to adjust for latent heat recovery were not available to us, but field data gathered for this project suggests that the analyzers add about 3 percentage points of efficiency for each 10 F^{o} drop in flue gas temperature below 120 ^{o}F.

Testo analyzers in the U.S., however, do not consider latent heat recovery, and consequently will not indicate an SSE above about 89 percent.[7] As we will show later, there is a substantial difference between the indicated SSE of the Testo analyzers and Bacharach analyzers when the exhaust flue gas is below about 120^{o}F.

Under the AFUE test procedure, condensate is collected and weighed. Moreover, the latent heat recovery under AFUE is based on cycling conditions rather than steady-state operation. Finally, AFUE also accounts for losses due to the fact that the warm condensate carries away some sensible heat—though this appears to have only a very small impact on the overall calculated efficiency.

It is difficult to know how significant the differences between these approaches are likely to be in terms of comparing SSE and AFUE. However, combustion expert Skip Hayden points out a couple of factors that may be important.[8] First, latent heat recovery per minute of operation may be higher under cycling conditions than under steady state operation. This is because the secondary heat exchanger is colder on start-up than it is under steady-state operation, and therefore is likely to condense water vapor at a higher rate. Second, Mr. Hayden notes that

[4] The most accurate protocol for these instruments is to first operate the furnace for five or ten minutes, then start the analyzer with the flue probe inserted in a hole in the intake air pipe near the furnace cabinet to get an accurate measurement of actual intake air temperature.

[5] About 9.5 percent of the higher heating value of natural gas is in the form of water vapor. Also, it is whether the latent heat contained in this water vapor is considered in the heating value of the fuel that forms the difference between what is known as "gross" versus "net" efficiency. Gross efficiency includes the latent heat in the heating value, while net efficiency excludes it. AFUE and the SSE reported by most combustion analyzers in the U.S. are in terms of gross efficiency (some U.S. analyzers are switchable between the two). Many European countries use net efficiency, with the somewhat counterintuitive result that condensing equipment can have a measured net efficiency that is greater than 100 percent.

[6] Personal communication with Joe Korva, Test Products International (12/15/06) and Rudy Leatherman and Dave Demicko, Bacharach, Inc. (01/03/07).

[7] Personal communication with Bill Spone, Testo, Inc., (01/02/07).

[8] Personal communication with Skip Hayden, Advanced Combustion Technology Laboratory, Natural Resources, Canada (01/08/07).

condensation is not necessarily equal across all channels of the secondary heat exchanger: for some furnaces, some heat exchanger channels condense a significant amount of water vapor while others do not. This can lead to a situation where more condensation actually occurs than would be indicated based on the aggregate temperature of the flue gas downstream of the heat exchanger. Both of these scenarios—but especially the former—suggest that latent heat recovery under AFUE may be higher than that indicated by SSE measurements of the aggregate combustion products that exit the unit.

Heat-up and cool-down losses
The AFUE test procedure incorporates procedures and equations to measure heat lost during the start-up and shut-down phases of furnace operation—losses that are not accounted for in SSE measurements. However, ASHRAE Standard 103-1993 allows for these losses to be omitted for units "…with no measurable airflow through the combustion chamber and heat exchanger during the burner off-period and having post-purge periods of less than 5 seconds…"[9] Most of the replacement furnaces installed under the weatherization program probably meet these criteria, and thus probably have AFUE ratings that assume zero start-up and shut-down losses. Nonetheless some units may exceed the five-second post-purge limit, and thus may have AFUE ratings that are slightly reduced due to start-up and shut-down losses.[10] These losses would not be reflected in SSE measurements.

Field Measurements of SSE

We made field measurements of SSE and other furnace operating parameters at nine sites for this investigation (Table 1). Five of these sites had previously failed a quality-control (QC) visit by registering an SSE more than two percentage points below the unit's rated AFUE. The other four sites were included because they were Ducane or York units that agency staff had reported as testing low on SSE during the current contract year.

For the investigation, we re-tested the SSE of the units, and checked for furnace temperature rise, airflow, external static pressure and gas supply pressures. We measured combustion parameters for each furnace simultaneously with three combustion analyzers. Two of the analyzers (Bacharach PCA, and Bacharach Fyrite Pro 125) were used for all nine sites. The remaining SSE test came from either a Testo 325M or a Bacharach Fyrite Tech 50 supplied by local agency staff. The SSE tests were made by measuring exhaust oxygen content and temperature near the exit from the furnace cabinet, and by measuring intake air temperature near the cabinet entrance (for analyzers that had the capability of measuring intake air temperature separately). We also measured intake and exhaust temperatures at the furnace cabinet with an accurate Fluke thermometer and outside at the venting terminations with Hobo Pro data loggers. Finally, we tracked condensate production using a tipping bucket and data logger apparatus.

Our test procedure called for recording the combustion analyzer readings at 2, 4, 6, 8, 10, 15, 20, 25, and 30 minutes following burner ignition. This sequence was interrupted at Sites 1, 3 and 8 when the burner shut down prematurely. At Site 1, the burner shut down shortly after the 20-

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[9] Section 9.10.
[10] Product literature for one of the units tested for this project (Site 3, Evcon (Coleman) Model GF9S) documents a 15-second post-purge.

minute mark, because the thermostat was satisfied. At Site 3, the burner shut down intermittently between Minutes 15 and 30: the cause of this behavior is unknown. The furnace at Site 4 also shut down intermittently between 15-25 minutes for unknown reasons. At Site 8, the household thermostat was satisfied when it switched to a setback program about 18 minutes into the test, causing the burner to shut down. At this site, we re-started the furnace and took a couple of additional readings extending beyond the 30-minute mark.

The figures on the following pages show key combustion analyzer data for the sites. The final figure plots the recorded SSE against measured exhaust temperature for all tests at all sites. A number of interesting observations can be made from these figures:

- The Bacharach PCA and the Fyrite Pro were in close agreement, except for Site 1 where there is a largedifference in SSE that appears as a significant anomaly in Figures 1 and 6. We suspect that the external thermocouple recording intake air temperature was configured incorrectly at this site.

- As Figure {} shows, SSE's recorded by the Testo analyzer begin to diverge from the other analyzers when the measured exhaust temperature is drops below about 120 ^{o}F (around the dew point of natural gas combustion products). This represents the transition point below which the SSE algorithms for the Bacharach analyzers provide SSE "credit" for latent heat recovery from condensation of water vapor in the combustion products while the Testo does not. For this reason, SSE's measured at exhaust temperatures below about 115 ^{o}F are significantly lower for the Testo instrument (Sites 4 and 5), while those measured at higher exhaust temperatures (Sites 2, 6 and 7) are comparable.

- SSE's measured by the Bacharach Fyrite Tech (Sites 8 and 9) were somewhat higher than those measured by the other two instruments. This is likely due to the fact that intake air temperature is based on the temperature of the flue gas probe at startup for Tech instrument (the home's basement in this case of Site 8 and the outdoor temperature for Site 9) rather than the actual air temperature of the incoming combustion air stream.[11]

- SSE readings changed over the duration of the testing: some furnaces showed high SSE's intitially that came down over time, and some showed lower values that increased over time. The readings became relatively stable after about ten minutes of operation.

- SSE's (excluding the Testo readings) at three of the five sites that had previously failed a QC SSE test (Sites 3, 8 and 9) were substantially higher (and within 2 percentage points of AFUE) after 10+ minutes of operation, suggesting that SSE readings for condensing furnaces can be sensitive to how and when the measurements are taken. (Note that the prior SSE reading for Site 3 matches those recorded by us for the first four minutes of operation: in this case, it may have been a matter of the prior reading being taken within

[11] Note that the Tech instrument did provide a separate measure of ambient basement temperature, plotted here as "intake" air temperature. Since the probe was inserted in the hot exhaust gas at this time, that measurement must have come from a sensor in the analyzer body. The indicated temperature increased over the course of the tests due to proximity with the increasingly warm furnace cabinet—more so for Site 8, where the analyzer was affixed to the supply plenum, than Site 9, where it was lying on the basement floor.

the first five minutes of operation, when the indicated SSE was lower for this unit.)

- The other two units (Sites 6 and 7) that had failed a QC SSE test showed SSE's that were on the borderline of being more than 2 percentage points below AFUE both for the QC test and during our re-testing. The AFUE of these Heil units at 90 percent was the lowest of any of those tested we tested, and are suggestive of lower latent heat recovery: it may be that differences between AFUE measurements of actual condensate production under cycling and the estimates of latent heat recovery from the analyzers are more pronounced for these units. It is also possible that these units were both sub-performing in the field.

- Site 2 showed the largest difference between tested SSE and AFUE, with tested SSE about four percentage points below rated AFUE. We found nothing anomalous about this unit, which was producing condensate under flue gas temperatures that were right around the dewpoint. Here again, there may be an issue with analyzer estimates of condensate production versus actual production.

- Sites 2, 6, 7 noted above (which all had measured SSE 2 or more percentage points below AFUE), also showed continuingly increasing exhaust temperatures over the duration of the test. This also suggests that condensate production under the cycling procedure in the AFUE test may lead to higher latent heat recovery than that obtained under steady-state operation.

- The furnaces were generally within manufacturer's specifications for all parameters except for external static pressure, which exceed specifications for all units. Although ESP exceeded specifications, airflow was sufficient that all of the units were well within specifications for temperature rise.

Table 1, Site details and measured operating parameters.

Site	Test date	Agency	BID	Make	Model	Rated AFUE	Prior SSE test	Input (kBtu/hr) rated	Input (kBtu/hr) measured
1	11/30	WDRY	10933	York	PS9A12N040UP11A	92.2	---	40	38
2	11/30	WDRY	10948	Ducane	CMPE075U3B	92.0	---	75	68
3	12/8	NCNT	38802	Evcon	GF9S080B12UP11H	92.0	88.4	80	86
4	12/13	PART	45326	York	GY9S060B12UP11J	92.0	---	60	62
5	12/13	PART	46175	York	GY9S080B12UP11J	92.0	---	80	77
6	12/13	LCSA	38639	Heil	N9MP2075B12C1	90.0	87.6	75	68
7	12/13	LCSA	34887	Heil	N9MP2050B12C1	90.0	88.4	50	---
8	12/14	SDC	38060	Payne	PG9MAA036080	92.1	87.4	80	103
9	`12/14	SDC	37815	Payne	PG9MAA036080	92.1	86.7	80	---

Site	Temperature rise [F°] spec.	Temperature rise [F°] measured	Airflow (cfm)	Ext. static pressure [Pa] spec. max.	Ext. static pressure [Pa] measured	Gas supply pressure [in.] spec.	Gas supply pressure [in.] measured	Gas manifold pressure [in.] spec.	Gas manifold pressure [in.] measured
1	35-65	47	780	125	256	4.5 – 10.5	---	3.5	---
2	40-70	49	970	125	185	4.5 – 10.5	7.4	3.5	3.1
3	45-75	62	---	125	150	4.5 – 14.5	---	3.5	---
4	40-70	44	755	125	145	4.5 – 10.5	---	3.5	---
5	40-70	56	810	125	205	4.5 – 10.5	7.2	3.5	3.2
6	40-70	59	850	125	160	4.5 – 14.0	7.19	3.5	3.03
7	40-70	57	610	125	255	4.5 – 14.0	7.24	3.5	3.13
8	40-70	---	875	125	180	4.5 – 13.6	7.24	3.2-3.8	3.12
9	40-70	52	660	125	155	4.5 – 13.6	7.24	3.2-3.8	3.12

(yellow) = measured value not within manufacturer's specifications. "---" indicates missing data.

Figure 1, Indicated SSE versus elapsed time and rated AFUE, by site.

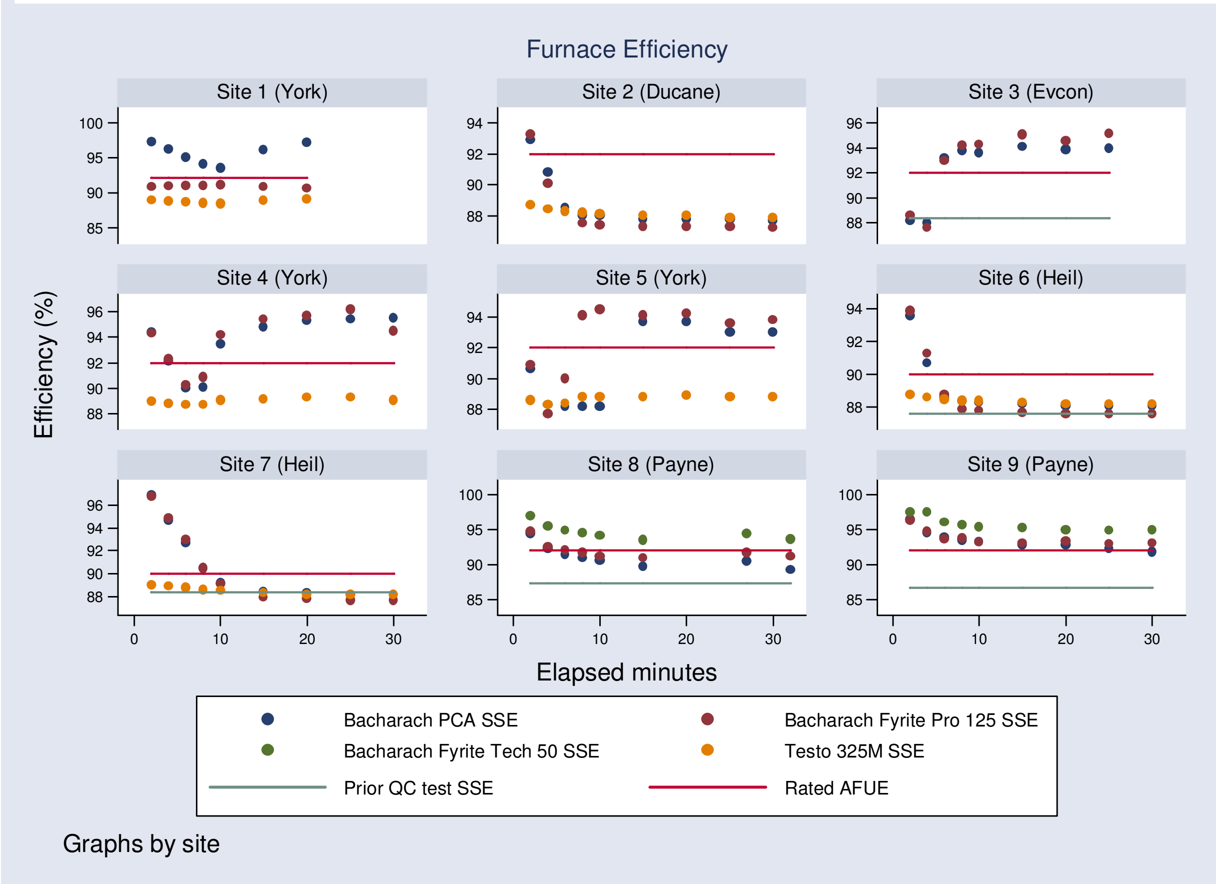


Figure 2, Measured Flue gas oxygen content versus elapsed time, by site.

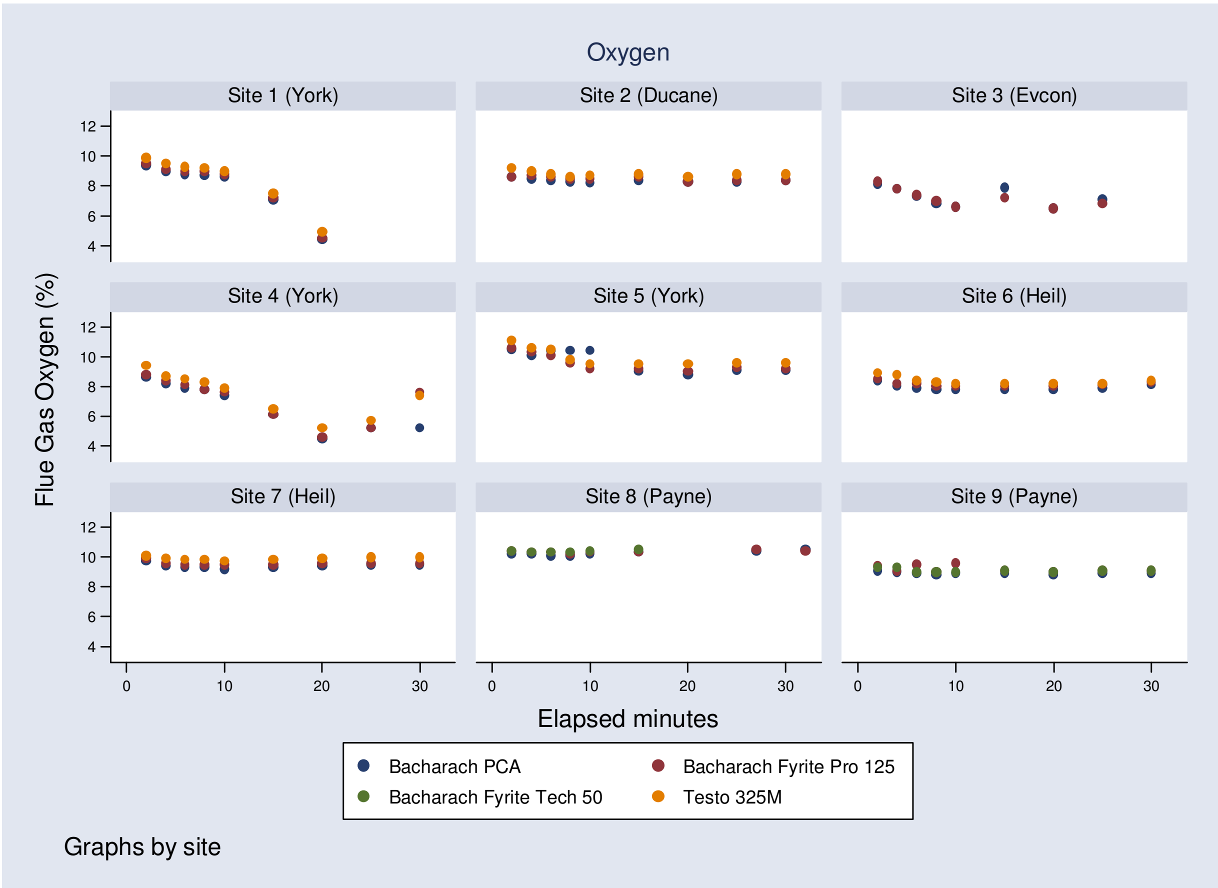


Figure 3, Indicated excess air versus elapsed time, by site.

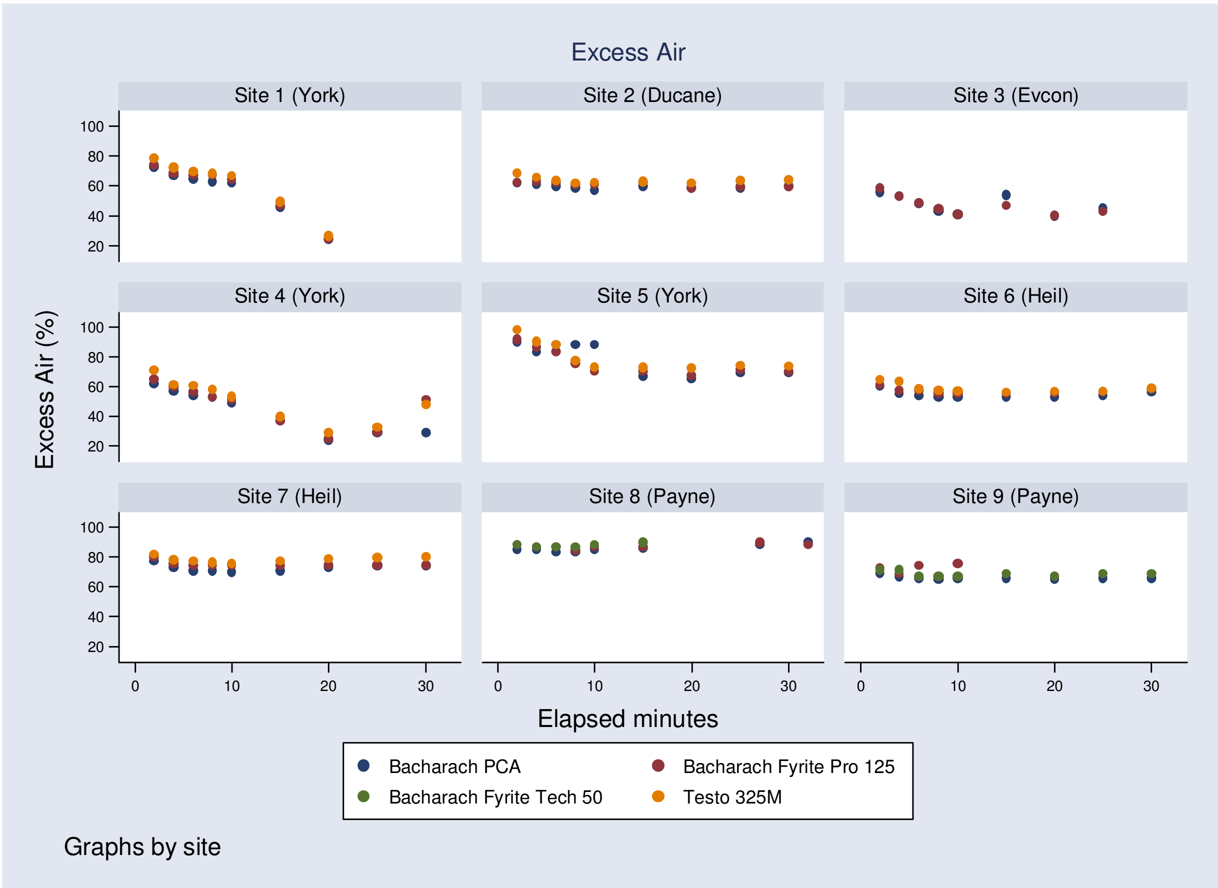


Figure 4, Measured flue gas exhaust temperature versus elapsed time, by site.

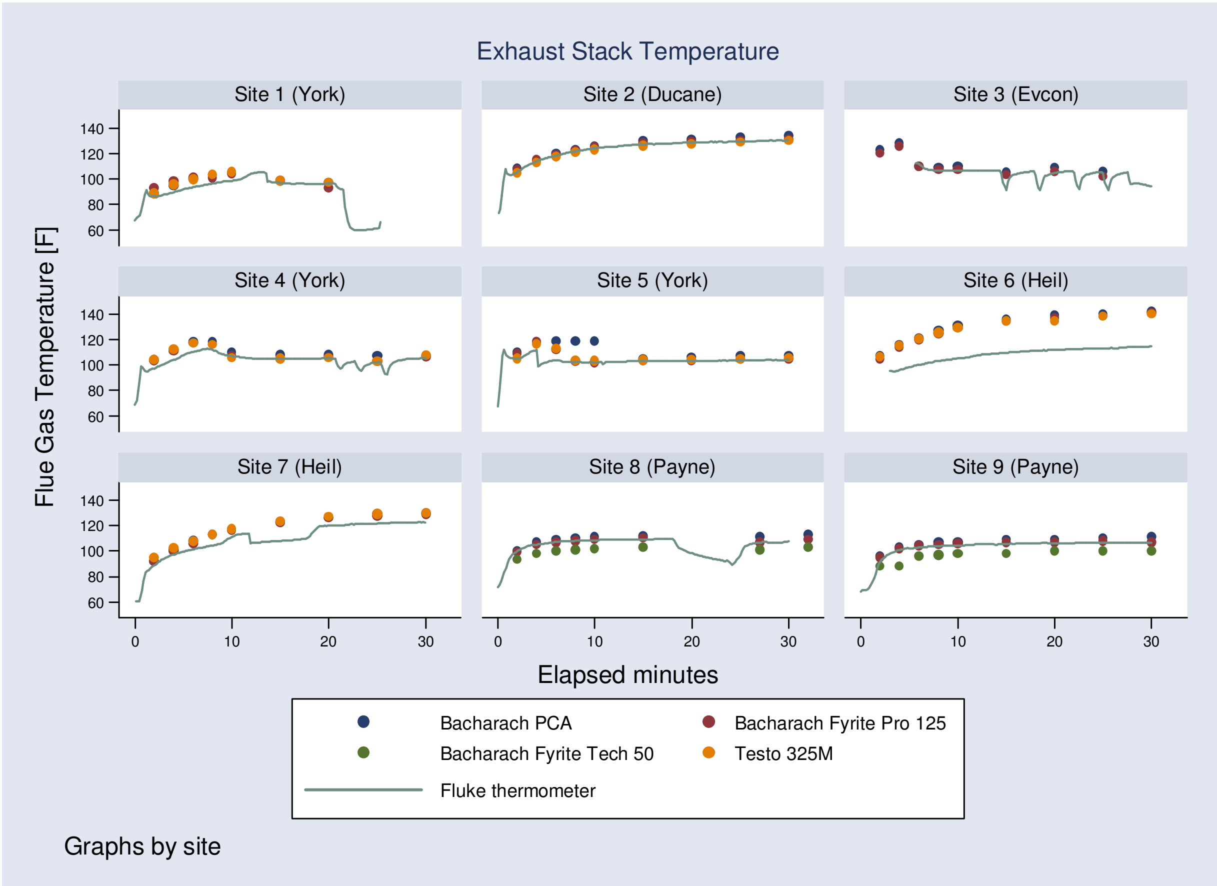


Figure 5, Measured combustion air intake temperature versus elapsed time, by site.

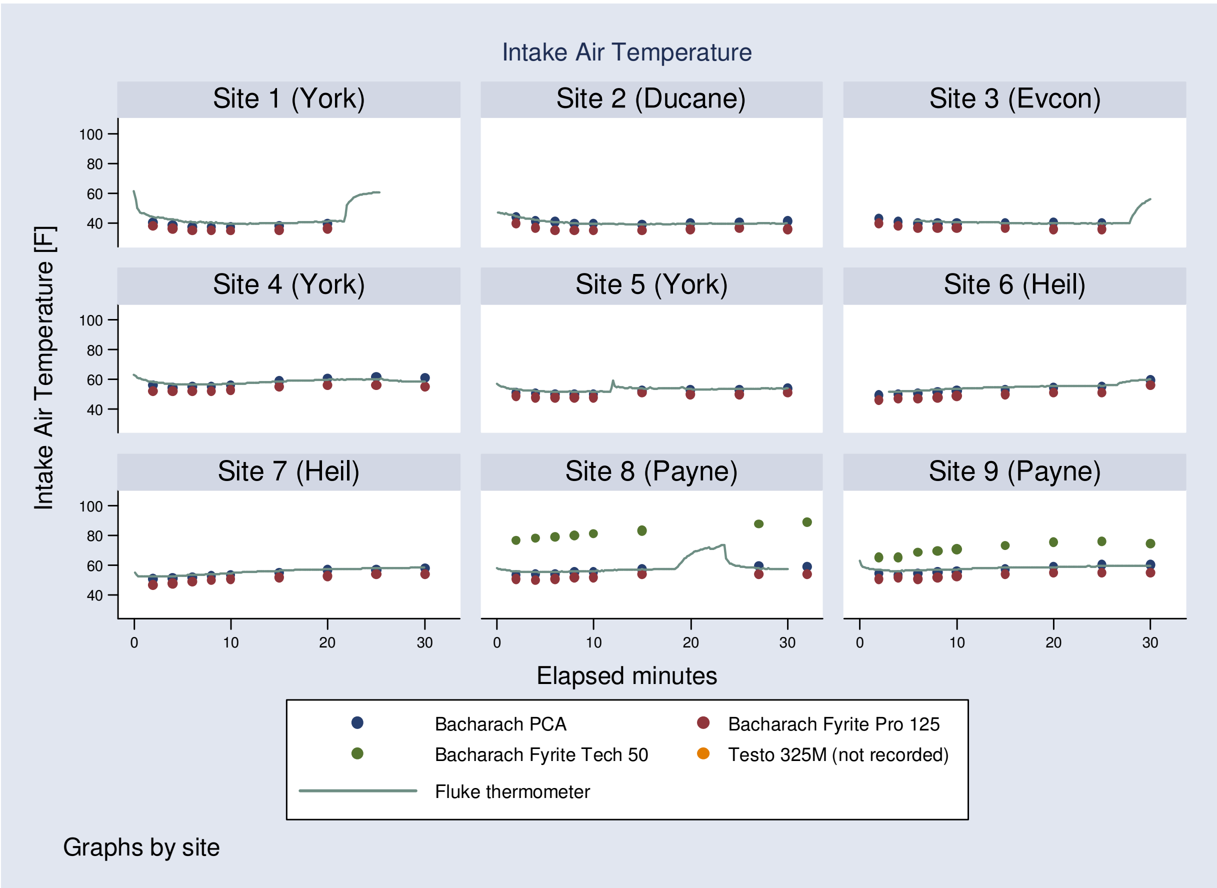
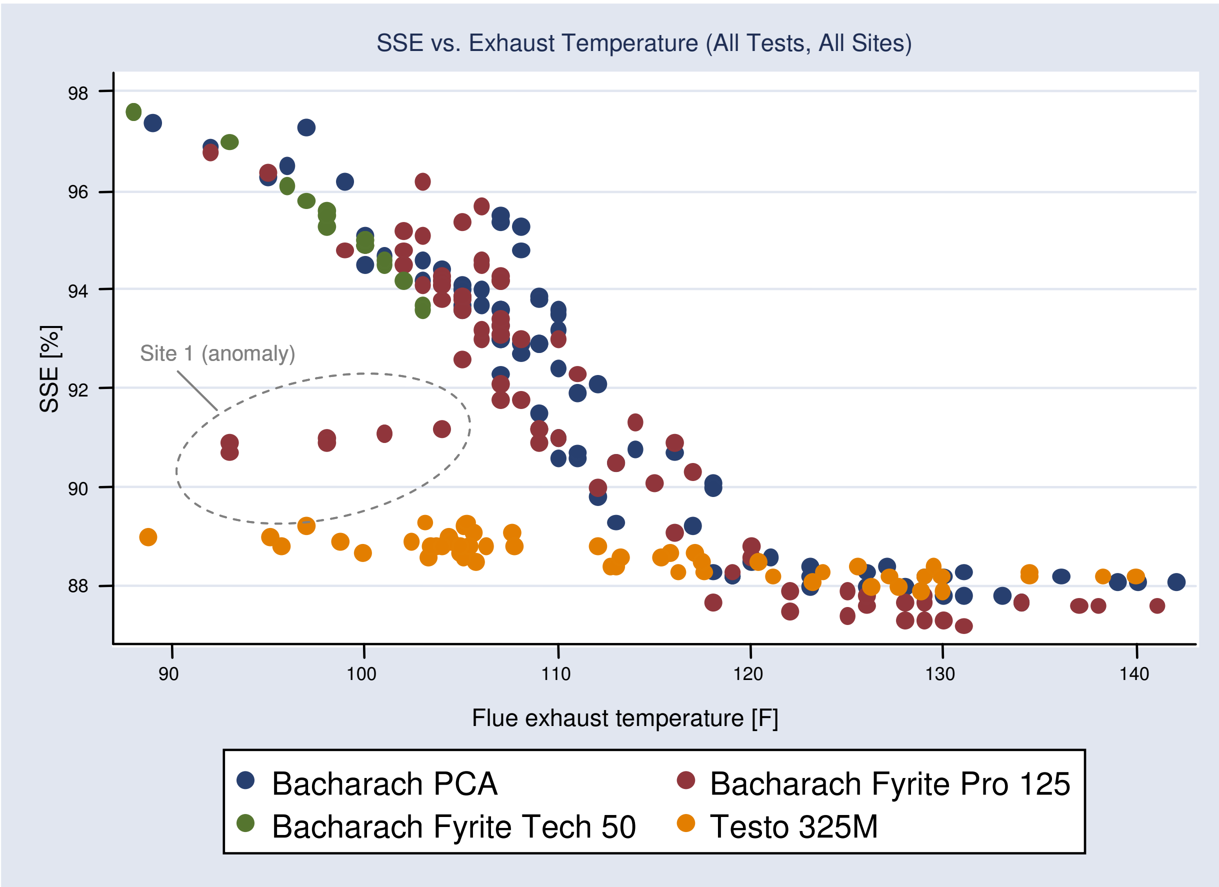


Figure 6, Indicated SSE versus stack temperature (all sites, all instruments).



Accuracy of Combustion Analyzers

Finally, we looked into the issue of how the field accuracy of the combustion analyzers' sensors translates into uncertainty in the indicated SSE. The oxygen sensor accuracy is listed as ± 0.3 percentage points for the Bacharach PCA and TPI Models 708-714, and was listed as ± 0.2 percentage points for the Testo 325M.

We found less information on the accuracy of the thermocouples used to measure stack and intake temperatures: the Bacharach PCA has a listed accuracy of ± 4 F^o for stack temperature (in the range of stack temperatures typical of condensing furnaces), and ± 2 F^o for the intake air sensor. The accuracy of the stack temperature probe is listed as ± 0.9 F^o for the Testo 325M.

At the upper end of these ranges (±0.3% oxygen, ± 4 F^o stack temperature, and ± 2 F^o intake temperature), the uncertainty in *sensible* heat loss is only about 0.15 percentage points. However, the strong relationship between indicated SSE and stack temperature in the condensing range shown in Figure 6 suggests that ± 4 F^o uncertainty in stack temperature translates into about 1.3 percentage points of uncertainty in *latent* losses. This suggests that the overall uncertainty in SSE for condensing operation is about ± 1.5 percentage points due to the accuracy limits of the sensors. There may also be additional inaccuracy from instruments that are out of calibration, but we did not investigate that angle in detail.