New York State Energy Research and Development Authority

Review of EPA Method 28 Outdoor Wood Hydronic Heater Test Results

Final Report

September 2011

No. 11-17

nyserda Energy. Innovation. Solutions.

NYSERDA's Promise to New Yorkers:

New Yorkers can count on NYSERDA for objective, reliable, energy-related solutions delivered by accessible, dedicated professionals.

Our Mission: Advance innovative energy solutions in ways that improve New York's economy and environment.

Our Vision: Serve as a catalyst—advancing energy innovation and technology, transforming New York's economy, and empowering people to choose clean and efficient energy as part of their everyday lives.

Our Core Values: Objectivity, integrity, public service, and innovation.

Our Portfolios

NYSERDA programs are organized into five portfolios, each representing a complementary group of offerings with common areas of energy-related focus and objectives.

Energy Efficiency & Renewable Programs

Helping New York to achieve its aggressive clean energy goals – including programs for consumers (commercial, municipal, institutional, industrial, residential, and transportation), renewable power suppliers, and programs designed to support market transformation.

Energy Technology Innovation & Business Development

Helping to stimulate a vibrant innovation ecosystem and a clean energy economy in New York – including programs to support product research, development, and demonstrations, clean-energy business development, and the knowledge-based community at the Saratoga Technology + Energy Park.

Energy Education and Workforce Development

Helping to build a generation of New Yorkers ready to lead and work in a clean energy economy – including consumer behavior, K-12 energy education programs, and workforce development and training programs for existing and emerging technologies.

Energy and the Environment

Helping to assess and mitigate the environmental impacts of energy production and use – including environmental research and development, regional initiatives to improve environmental sustainability, and West Valley Site Management.

Energy Data, Planning and Policy

Helping to ensure that policy-makers and consumers have objective and reliable information to make informed energy decisions – including State Energy Planning, policy analysis to support the Low-Carbon Fuel Standard and Regional Greenhouse Gas Initiative, nuclear policy coordination, and a range of energy data reporting including *Patterns and Trends*.

Review of EPA Method 28
Outdoor Wood Hydronic Heater Test Results

Final Report

Prepared for the

New York State
Energy Research and
Development Authority

Albany, NY
www.nyserda.org

Nathan Russell
Assistant Project Manager

Prepared by:
Brookhaven National Laboratory
Dr. Tom Butcher

and

Nathan Russell
Assistant Project Manager

NYSERDA
Report 11-17

NYSERDA

September 2011

Notice

Preface

EPA began Phase II of the Voluntary Hydronic Heater Program after October 15, 2008. To qualify under this "White Tag" program, appliances are tested using EPA Method 28 Outdoor Wood Hydronic Heater (M28 OWHH) and must achieve a weighted emissions rate of 0.32 lb/mmBtu (output) less. In late 2010, EPA recognized that the efficiency values determined using M28 OWHH did not represent actual efficiencies of qualified White Tag units and removed the efficiency values from the website while the issue was reviewed.

The work described in this report was conducted as a screening-level review of the M28 OWHH test results for the 23 units that were qualified under Phase II of the program at that time. Personnel from Brookhaven National Laboratory, NYSERDA, the Northeast States for Coordinated Air Use Management (NESCAUM), New York State Department of Environmental Conservation (NYSDEC), Vermont Department of Environmental Conservation, Maine Department of Environmental Protection, and Massachusetts Department of Environmental Protection participated in the review of the White Tag qualification data to identify possible sources of error.

Concurrent to this effort was EPA's stakeholder process to make improvements to M28 OWHH that included representatives from state air agencies, NYSERDA, and BNL as well as manufacturers in the Voluntary Program and the commercial test laboratories that conducted the original tests. Many of the recommendations found in this report have already been implemented in EPA's test method revision, Method 28 Wood Hydronic Heater (M28 WHH).

Acknowledgments

This research was supported by the New York State Energy Research and Development Authority. NYSERDA acknowledges the contribution of Louis Fontaine, Maine Department of Environmental Protection; Phil Etter, Vermont Department of Environmental Conservation; Marc Cohen, Massachusetts Department of Environmental Protection; Randy Orr and John Barnes, NYSDEC; Lisa Rector, NESCAUM, and Chris Brown, BNL. We also acknowledge extensive dialogue on these test results coordinated by the EPA to modify the test method. Participants included the EPA accredited test labs, manufacturers of OWHHs as well as those listed above. The modified test method M28 WHH which resulted from EPA's stakeholder process can be found on the Burn Wise website.

Table of Contents

List of Figures

List of Tables

Glossary

Appliance (Hydronic heater or Supply) side—Everything to the left of the heat exchanger in Figure 1. This is a closed loop system.

Aquastat—A control device for the heater that determines when it turns on and off and determines the temperature of the water leaving the heater.

Closed Loop—A system of piping where the water is recirculated. For example on the hydronic heater side, water leaves the hydronic heater, passes through the heat exchanger, and returns to the hydronic heater to be reheated.

Condensing operation—Occurs when the heat exchanger or flue surface temperatures are below the flue gas dew point causing primarily water vapor to condense on the cooled surfaces. Condensing increases efficiency, however, the condensate is corrosive. If it occurs for extended periods of time the hydronic heater will fail prematurely due to corrosion of hydronic heater components. Condensing becomes a concern when return water temperatures are below 130 F and the degree of condensing increases as return water temperature is reduced.

CSA B415—Canadian Standard B415. This standard is analogous to Method 28 OWHH and used to evaluate the performance of hydronic heaters.

Design Day Load—This is the highest heating load the building is expected to see and should be used to properly specify the hydronic heater size. To be accurately estimated an analysis of the building design is necessary to evaluate such characteristics as: square footage, windows, air leakage, insulation, orientation, solar gain, climate, and so on. Using only square footage can provide extremely inaccurate results.

Load (Cooling Water) Side—Everything to the right of the heat exchanger in Figure 1. Typically, cooling water is sourced from city supply or a well, passes through the heat exchanger, and is drained. It provides a medium to transfer energy (heat) from the hydronic heater loop.

M28 OWHH—Method 28 Outdoor Wood Hydronic Heater. The test method for evaluating hydronic heaters.

M28 WHH—Method 28 Wood Hydronic Heater. Revised version of M28 OWHH.

Nominal Output—The maximum hourly output of the hydronic heater.

Open loop—A system of piping where recirculation does not occur. The load side is typically open loop.

Stack Efficiency—Efficiency as determined using the temperature and gas concentrations of the exhaust and the chemical composition of the fuel (wood).

Thermal Efficiency—Efficiency as determined using the input/output method described in M28 OWHH

Thermal Storage—Typically a large water-filled tank that serves as a buffer between the building heat load and the heater output. It can rapidly absorb the energy from the heater and gradually release it as it is needed thereby allowing the heater to operate at higher loads for the majority of the time.

Thermopile—A series of thermocouples used to measure a temperature difference. Accuracy is improved over measuring the temperature difference using only two thermocouples..

Two-stage unit—A specific design of hydronic heater that enables the combustion process to be split into two stages. Typically there are two combustion chambers for split-wood units. In the first stage, combustion occurs under oxygen starved conditions at relatively low temperatures to promote gasification of the volatile compounds. In the second stage the gases are combusted under oxygen rich conditions at relatively high temperatures to promote complete combustion. Typically an oxygen and/or temperature sensor is used to support optimum operation.

Executive Summary

Under a Hydronic Heater Voluntary Partnership Program, the U.S. EPA has developed Test Method 28 OWHH for Measurement of Particulate Emissions and Heating Efficiency of Outdoor Wood-Fired Hydronic Heating Appliances (known as M28 OWHH) for evaluation of the particulate emissions and efficiency of wood-fired hydronic heaters. Currently 23 units have been approved under the Phase II emission levels of this program. Meeting this Phase II level requires achieving an annual average particulate emissions rate of 0.32 lb/MMBtu heat output or less. As part of the M28 OWHH testing, the thermal efficiency of the units is reported. Recently, significant concerns were raised due to the reported efficiencies for some of the units being questionably high. The EPA suspended qualification of units in the Voluntary Program until the source of the error could be determined and remedied.

Figure 1 shows the generic hydronic system arrangement in the M28 OWHH test. The test installation is arranged to enable measurement of energy output from the hydronic heater on both the supply (appliance) side of the heat exchanger shown or on the load (cooling water) side. Energy input is based on the heating value of the wood and the amount consumed based on the change in the mass of the hydronic heater during a test. Efficiency is simply energy output divided by energy input. Energy output is based on the supply side water flow rate and temperature change across the heat exchanger. Energy output can also be measured based on the load or cooling water side flow rate and temperature rise across the heat exchanger and these measurements were included in the test method to provide a quality control check on the test results.

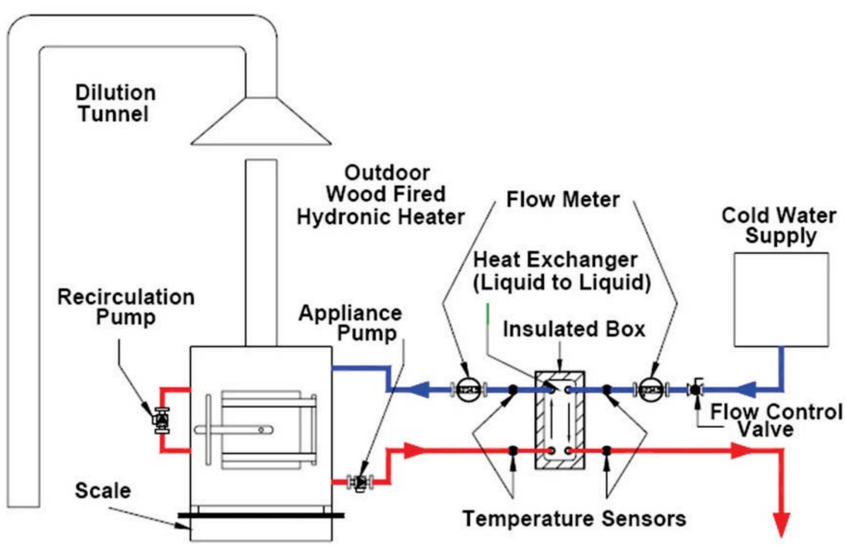

Figure ES-1. Generic piping arrangement in Test Method 28 OWHH. The appliance (also hydronic heater or supply) side is to the left of the heat exchanger while the load side is to the right of the heat exchanger.

Manufacturers seeking to be partners in the Voluntary Program are required to submit the qualification test data, via independent test labs, to EPA for review and approval. A request was made to EPA for the data from qualified White Tag wood hydronic heaters and personnel from the Northeast States for Coordinated Air Use Management (NESCAUM), Brookhaven National Lab (BNL), New York State Energy Research and Development Authority (NYSERDA), New York State Department of Environmental Conservation (NYSDEC), Vermont Department of Environmental Conservation, Maine Bureau of Air Quality, and Massachusetts Department of Environmental Protection reviewed the data in order to identify possible sources of error that could explain the high efficiencies. Many aspects of the data were analyzed including: testing parameters such as water temperatures, flow rates, stack temperatures, and wood moisture content; precision requirements related to flow meters and temperature sensors; and efficiency and emissions calculations on the hydronic heater side compared to the load side of the heat exchanger in the test apparatus. The group did not review aspects of particulate measurements. Efficiency was also estimated via a stack loss analysis for comparison with the reported results. In some cases parameters had to be estimated for the stack loss analysis as they were missing from the obtained test data. The efficiency based on stack loss as calculated in this analysis is reasonably accurate under steady-state conditions i.e. full load (Cat IV) testing and overestimates efficiency under cyclic loading such as in categories one through three (Cat I-III). Rather than using the efficiency based on stack loss analysis to establish an efficiency rating for a specific test, the purpose of this analysis was a high-level check to determine if any reported efficiencies for a test run in M28 OWHH were unreasonably high from a thermodynamic perspective. For this evaluation, any reported efficiency by M28 OWHH that was greater than two percent less than the combustion efficiency was considered thermodynamically impossible and a flag was raised on the analysis of the subject test run.

An underlying issue with M28 OWHH was the use of water temperature and flow rates from the supply side of the heat exchanger for determining hydronic heater output energy. In this review it was often found that the supply side temperature drop across the external heat exchanger was low and water flow rate was high, particularly when test runs conducted at lower firing rates were evaluated. This in turn led to an increase in error of the output calculation. For example, in one case the temperature drop across the heat exchanger was only one degree while the precision of the temperature sensor was half a degree thereby providing an error of 50%. However, on the load side of the heat exchanger, it is possible to maintain low flow rates (although high enough with respect to flow meter precision) and high temperature differences relative to the precision of the measurement instruments thereby reducing the error associated with the efficiency measurement drastically. There was often a significantly large difference between the energy output values determined using measurements from the hydronic heater side of the heat exchanger compared to the efficiency values determined using measurements from the load-side of the heat exchanger.

The review of M28 OWHH test results was performed at the screening level and the intent was to identify any test results where a more in depth analysis may be warranted. The M28 OWHH test results of (23) qualified hydronic heater units were evaluated and 21 (90%) were found to have missing or questionable data. The specific test issues included missing data, testing outside of the prescribed heat-load categories, and error associated with temperature and flow measurements described above. The specific recommendations to reduce uncertainty and improve quality control on M28 OWHH from this analysis are as follows:

- Use the water temperature and flow rates from the load side of the heat exchanger for energy output measurements. The error associated with the precision of the instruments is drastically improved (reduced) due to lower flows and higher temperature differences across the heat exchanger
- Integrate overall efficiency calculations based on the CSA B-415 Stack Loss Method as a quality control check on efficiency ratings. An input/output method for annual efficiency based on M28 OWHH load side measurements should still be the primary method

- Revise measurement and calculation methods for wood fuel moisture. Ensure the moisture content of the wood is accurately recorded by increasing the number and locations of measurements. EPA is considering a rigorous evaluation of the wood moisture and energy measurement method as part of the New Source Performance Standard
- Specify the hydronic heater temperature range to avoid possible condensing conditions that become a concern at return water temperatures less than 130 °F. Condensing will improve efficiency ratings for the test, however, if the hydronic heater is not designed for condensing but operated under such conditions, it will fail prematurely due to corrosion within the hydronic heater itself. Consider requiring typical operational settings for traditional hydronic heating systems: supply temperature 180 °F (range 160-200 °F) and return temperatures 160 °F (range 140-170 °F)
- Revise methods for temperature and flow measurements. Use a thermopile for temperature measurements to improve accuracy. Place the flow meter on the input side of the load side as the temperature of the water entering the heat exchanger should be reasonably constant
- Revise the frequency for data collection from 10 minutes to < 15 seconds for values such as water temperatures, flow rates, stack temperature and gas concentration. Temperature changes of >10 degrees were observed over a ten minute period. During cycling a ten minute period may not adequately represent the peaks and valleys of the cycle. A shorter time period will allow a better output measurement
- Ensure water density calculations are based on the temperature nearest the flow meter and that the water density is based on temperatures over the data collection period (i.e. 15 seconds) as opposed to the average for the entire test (i.e. eight hours)
- Require reporting of CO_2 data. This will help to characterize combustion performance and provide a check on efficiency values
- Require reporting of CO data. CO presents a safety concern and is particularly important for units installed indoors that will become more common in the market and are tested under M28 WHH. Similar to CO_2, it also characterizes combustion performance.

In light of the development of the New Source Performance Standard (NSPS) that is currently underway, this report contains a section that compares and contrasts the emissions and efficiency values determined using the four M28 OWHH categories with those that would result from substantial revisions (SR) to weighting factors and load limits. These methods differ in the load on the hydronic heater for their respective test categories. While M28 OWHH uses four categories with the lowest being <15% full load, the SR method uses only three with the lowest being <35% full load. Moreover, in M28 OWHH, the lowest load (category I) is weighted the most of all four categories due to the amount of time OWHHs spend at idle. Moving to fewer and higher loads in the test method creates a situation in which the test method is even less representative of actual operating conditions. Because emissions generally increase significantly with decreasing load on the heating system, even exponentially higher (Figure 2), removing the lowest load from the test will greatly reduce the calculated average emissions rate for the hydronic heater. Using data from 20 of the hydronic heater tests, overall efficiency was found to increase by more than 5% and the emissions rate decreased by 0.048 lb/MMBtu representing a greater than 19% average reduction in emissions ratings when the M28 OWHH test data from categories II, III, and IV were used to determine the efficiency and emissions ratings per SR method.

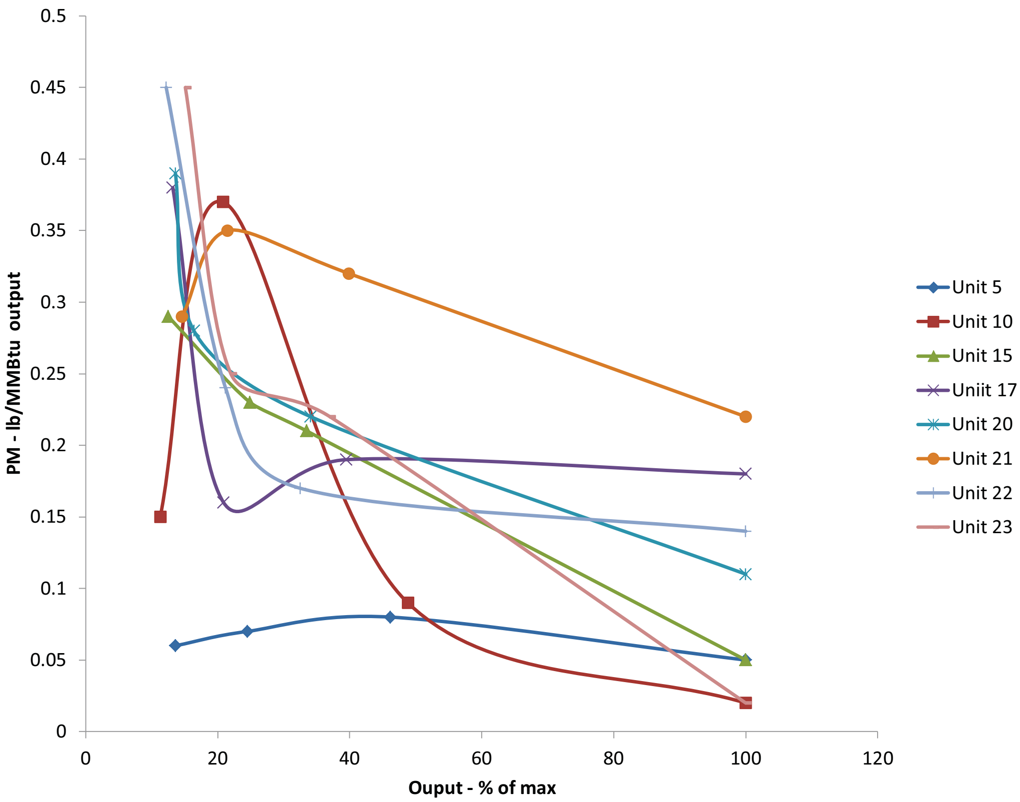

Figure ES-2. Illustration of reported particulate emissions vs. output for selected units. Emissions generally increase significantly with decreasing load on the heating system, even exponentially higher below 25%. Removing the lowest load from the test via substantial revisions to the test method weighting factors and load limits will greatly reduce the calculated average emissions rate for the hydronic heater, creating a situation in which the test method is even less representative of actual operating conditions.

The section also investigates the impacts of hydronic heater output with respect to building design heat loads. The average output of the White Tag units when using the load side data is 175 kBtu/hr. Assuming representative design heat loads for a very cold (North Dakota), cold (New York), and moderate climate (Maryland) are 65, 40, and 20 kBtu/hr respectively leads to sizing factors ranging from 2.7—8.8 respectively. In the very cold climate this represents a maximum hourly heater output of 37% and 11% for a moderate climate. The design conditions typically occur for less than two percent of the year and for 90% of the time the heating load on the building is at 70% of the design load or less (BNL, 2004). For a very cold climate, the heater output will be at or below 26% for 90% of the time, similarly for the moderate climate the output will be at or below 7% for 90% of the time. Based on the trends in figure 2, operation at these loads can lead to a substantial increase in emission rates.

Finally, with respect to the NSPS, it is important to recognize that M28 OWHH was designed for a particular wood-fired heating technology, the outdoor wood hydronic heater. Two-stage combustion wood-fired heaters, designed with two distinct combustion chambers and oxygen and/or temperature sensors, combined with external thermal storage provide an opportunity to achieve much higher efficiency and lower average emission rates by avoiding cycling at low loads (NYSERDA 2011; 2010; 2010A). These units operate at much higher loads than OWHHs,

typically at greater than 50% load for cord-wood fired hydronic heaters and greater than 30% for wood pellet-fired hydronic heaters.

Concurrent with this effort was EPA's stakeholder process to make negotiated improvements to M28 OWHH that included representatives from state air agencies, NESCAUM, NYSERDA, and BNL as well as manufacturers in the Voluntary Program and the commercial test laboratories that conducted the original tests. Many but not all of the recommendations found in this report have already been implemented in EPA's test method revision, Method 28 Wood Hydronic Heater (M28 WHH). Those recommendations that were not included in the M28 WHH revisions or those that were beyond the scope of the revisions are recommended for consideration as the NSPS is developed and include:

- Carefully consider the impact of sizing as it impacts the weighting factors for each load. As the hydronic heater nominal output increases with respect to the design load, the time spent at lower loads increases
- Carefully consider test category load limits, particularly with the lowest load limit. Emissions can decrease exponentially as loads are increased, which may artificially inflate performance ratings and stray farther away from representative operation
- Consider the applicability of the method, particularly the category load limits and associated weighting factors, with the next generation technology. Installing two-stage, gasification units with thermal storage promotes high output operation to avoid low outputs. The suitability of M-28 OWHH for testing 2-stage combustion units was the subject of another NYSERDA report (NYSERDA, 2010A). M-28 OWHH does not properly address these advanced technologies.

1 Introduction

Under a Voluntary Partnership Program, the U.S. EPA has developed Test Method 28 OWHH (M28 OWHH) for evaluation of the particulate emissions and efficiency of wood-fired hydronic heaters. Currently 23 units have been approved under the Phase II emission levels of this program. Meeting this Phase II level requires achieving an annual average particulate emissions rate of 0.32 lb/MMBtu heat output or less (US EPA, 2008).

Currently, several states are implementing regulatory programs that affect these same units. Some of these states established regulations that accept outdoor wood hydronic heaters qualified under the EPA Voluntary Partnership Program. A limited number of states have established their own certification programs, which may require additional review, and provides them with the flexibility to accept or reject results of prior M 28 OWHH tests under their individual state certification process.

The purpose of the study described here was to conduct a review of the available Method 28 OWHH (M28 OWHH) test results to evaluate: completeness of the data sets, consistency of the test results, error magnitudes where they can be estimated, and areas in which the test procedure can be improved. The analysis done in this review is considered to be at the “screening” level. It is intended to identify units where significant problems exist with the testing and for which more detailed review may be warranted.

2 Overview of Test Method 28 OWHH (M28 OWHH)

Under Method 28 OWHH, wood-fired hydronic heaters are installed in a test lab, on a weigh scale with a closed loop / heat exchanger arrangement for imposing a thermal load. At the present time a significant modification to M28 OWHH is nearing completion and the review discussed in this report is based on the method that has applied prior to these modifications.

Figure 1 shows the generic hydronic system arrangement in the M28 OWHH test. The test installation is arranged to enable measurement of energy output from the hydronic heater on both the supply (appliance) side of the heat exchanger shown or on the load (cooling water) side. Energy input is based on the heating value of the wood and the amount consumed based on the change in the mass of the hydronic heater during a test. Efficiency is simply energy output divided by energy input and output is based on the supply side water flow rate and temperature change across the heat exchanger. Energy output can also be measured based on the load or cooling water side flow rate and temperature rise across the heat exchanger and these measurements were included in the test method to provide a quality control check on the test results.

As part of the revisions to M28 OWHH, which are nearing completion, a decision has been made to change from using the supply side measurements to the load side water temperature and flow rate measurements for the energy output calculation. The primary motivation for this is the greater magnitude of the temperature change on the load side that provides greater accuracy in the overall calculation. In addition, since the load side is an open flow, it is easier to include regular calibrations of the flow measuring device against a weigh scale during a test program.

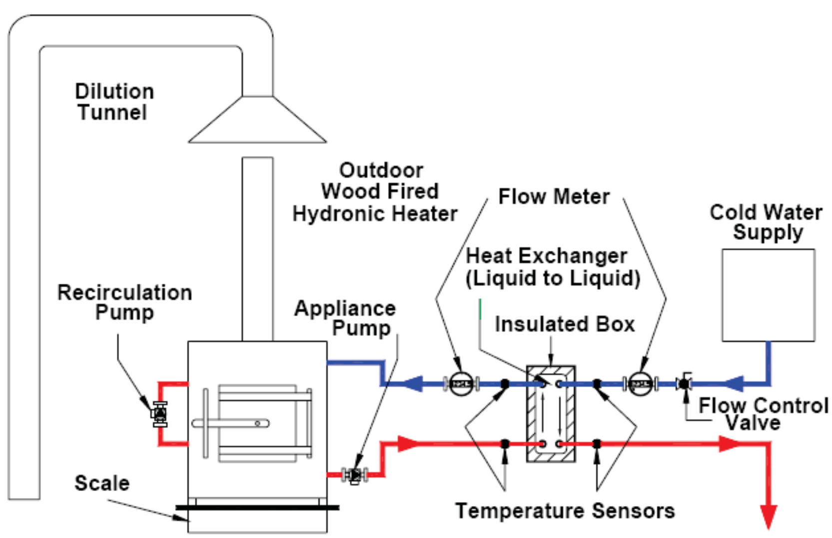

Figure 1. Generic piping arrangement in Test Method 28 OWHH. The appliance (also hydronic heater or supply) side is to the left of the heat exchanger while the load side is to the right of the heat exchanger.

In M28 OWHH, particulate emissions are measured using a dilution tunnel system as defined in ASTM E2515 Standard Test Method for Determination of Particulate Matter Emissions Collected in a Dilution Tunnel. The emissions rate is calculated by dividing the particulate matter mass by the energy output described above.

Testing is done with the heat output adjusted at four different levels as follows:

Category I: A heat output of 15% or less of Manufacturer's Rated Heat Output Capacity

Category II: A heat output of 16% to 24% of Manufacturer's Rated Heat Output Capacity

Category III: A heat output of 25% to 50% of Manufacturer's Rated Heat Output Capacity

Category IV: Manufacturer's Rated Heat Output Capacity

Testing is done "hot-to-hot" i.e.—at the start of each of the four test runs the hydronic heater is at operating temperature and the test is completed when the added fuel charge is consumed.

From the test data, annual values for both particulate emissions and efficiency are determined based on a weighted average of the results of each of the category tests. The weighting values are:

Category I: 0.437

Category II: 0.238

Category III: 0.275

Category IV: 0.050

The test method is intended to provide a replicable and common measurement method to rank appliance performance. It is not intended to necessarily represent the full range of potential variations in actual in-use operation of an OWHH. The defined test fuel is red or white oak that has 19 to 25% moisture content on a dry basis. Each piece is cut to a 4" X 4" cross section and the length was dependent on the firebox dimensions. Fuel heating value may be measured or a default value can be used.

3 Review of Test Results

A review of the reported test data for all 23 units has been performed. The approach taken was to conduct this at a screening level to provide a rapid comparison of the factors that may affect the accuracy of the reported results and compliance with the M28 OWHH test procedures. For some of the tests, data was available in a spreadsheet file that facilitates analysis. In other cases only a printed form of the raw test data was available.

In the review the focus was placed on the following categories:

- Accuracy of the energy output value calculated based on the supply-side water temperature and flow rate measurements
- Comparison of the energy output results determined by supply side and load side water temperature and flow rate measurements
- Comparison of reported efficiency with efficiency estimated from stack gas conditions for each category test
- Measured moisture content of the wood used in the test runs compared to the range specified by M28 OWHH
- Actual energy output relative to the specified energy output (i.e. load) in each category
- Recalculation of the particulate emissions rate based on load side output.

A discussion of each of these follows.

1. **Accuracy of Energy Output Based on the Supply Side Measurements**. In M28 OWHH it is specified that the supply side flow meter shall be "A totalizing type water flow meter with a resolution of 0.1 gallon and an accuracy of 2% of the volume recorded or a flow meter with an accuracy of ±0.1 gal/min." In the test reports, the supply side water flow rate ranges from 3.4 gpm to 21.7 gpm. Using the ±0.1 gal/min criteria, applied to the lowest flow rate, 3.4 gpm, the accuracy of this measurement is 2.9% and this is the highest it could be. For the purposes of this review it is simply assumed that the accuracy of the supply side flow measurement is 2%.

Energy output on the supply side is the product of flow rate multiplied by the temperature difference across the heat exchanger multiplied by the specific heat. M28 OWHH states that the "temperature difference measurement shall have an uncertainty of ±0.50 °F". The percentage error in the temperature difference measurement then can be taken as $100 \cdot \frac{0.5}{Delta\ T}$. Where $Delta\ T$ is simply the temperature difference across the heat exchanger on the supply side. This error can become quite significant when the Delta T is small.

2. **Comparison of the Energy Output Results Determined by Supply Side and Load Side Water Temperature and Flow Rate Measurements**. From the data reported for each unit test, a comparison can be made of the output determined from the supply side and load side flows and temperatures. These would not be expected to be identical but they should be closer than the range that would be achieved if both measurements were at the limits of accuracy prescribed in M28 OWHH. For the load side measurement, the accuracy required is specified by "A totalizing type water flow meter with a resolution of 0.1 gallon and an accuracy of 0.5% of volume recorded or a flow meter with an accuracy of ±0.01 gal/min". In the test data, load side cooling water flows range from a low of 0.118 gpm to 14.9 gpm. At the lowest flow rate an accuracy of ±0.01 gal/min in a flow meter would provide an accuracy of 8.5%. For the purposes of this review it has been assumed that the

accuracy of this flow is 0.5%, based on the requirement for a totalizing flow meter. The thermocouple accuracy requirement is the same as for the supply side.

For the purpose of the data review, the actual difference between the supply side and load side energy outputs was calculated and compared with the maximum possible difference, assuming that the measurements were made at the specified accuracy limits as discussed above. The expression for the maximum possible difference between the two output measurements, expressed as a percent, is:

$$MaxPercentDifference = \left\{2 + \frac{100 * 0.5}{SupplySideDeltaT}\right\} + \left\{0.5 + \frac{100 * 0.5}{LoadSideDeltaT}\right\}$$

Of the 23 White Tag qualified hydronic heater units for which test results were reviewed, two were eliminated from the process due to incomplete data. Of the remaining 21 units, 17 have a difference between the supply side and load side outputs that is greater than that determined from this equation, raising concerns about the accuracy of the results.

3. **Comparison of Reported Efficiency with Efficiency Estimated from Stack Gas Conditions**. For each unit and category test, the test reports include a value for the efficiency based on the supply side output results. In some cases these results are very high, over 90% and even exceeding 100% in one case, and therefore unreasonably high thermodynamically. To achieve efficiency levels this high the flue gas temperature would have to be very low and the units would be in a condensing mode. To provide a rough check on the reported efficiency levels, efficiency was calculated using a stack loss method. This approach assumes that the efficiency of the hydronic heater is 100 percent, minus losses that are associated with hot flue gas vented through the chimney. This calculation considers the ultimate analysis of the dry fuel (Carbon, Hydrogen, Oxygen, and Nitrogen), the actual as-fired moisture content, the flue gas temperature, and the excess air level as determined by the measured flue gas CO_2 concentration. This value for efficiency is higher than for the direct input/output measurement because it does not include jacket losses and does not consider energy lost with unburned fuel. For these reasons, if the efficiency, reported based on the supply side output measurements is higher than 2% less than the efficiency determined from the stack loss method in a steady state test, the results can be considered thermodynamically impossible. In some of the tests results reviewed, efficiency from the supply side output far exceeded the efficiency calculated from the stack loss method.

The heat losses in the stack were calculated using a program developed at BNL which included the following thermal factors:

$C_{pdg} = 1.00 \ \frac{kJ}{kg\ K}$ mean heat capacity of dry flue gas

$C_{pwv} = 1.91 \ \frac{kJ}{kg\ K}$ mean heat capacity of flue gas water vapor

$\lambda = 2257 \ \frac{kJ}{kg}$ latent heat of flue gas water vapor

For each Category test evaluated, the stack loss efficiency was based on a simple average of the flue gas temperature and CO_2. While this approach is reasonable for a high load test (i.e. Cat. 4), for other burn categories one would not expect to see stack loss calculations compare closely with measured efficiencies due to cycling. Nevertheless, for a cyclic test this is expected to bias the calculated stack loss efficiency to the high side and the measured efficiency

should never approach the calculated stack loss efficiency. With the purpose of identifying cases where the reported efficiency is higher than could be possible based on stack loss efficiency, this approach is seen as unlikely to incorrectly identify a case where the reported efficiency is too high. Based on this approach, the review flagged any category test where the efficiency reported was higher than efficiencies calculated with the stack loss method. For cases where the efficiency is seen as a key issue, a detailed analysis should be done in which flue gas temperature, CO_2, and fuel consumption rate during each reported time interval is analyzed to determine the run average stack loss efficiency. This was impractical in this case in part because only some of the data was provided in a spreadsheet file format with the balance provided in a printed table form. In addition, CO_2 was not reported for more than half of the units reviewed. In this case a typical excess air level, 30%, was assumed for the analysis.

4. **Actual Moisture Content of the Wood Used**. For each test, the reported average moisture content was compared to the M28 OWHH allowable range of 19-25% dry basis. With the exception of pellet units, the moisture content was always within this range. The method does not specify a moisture requirement for pellets and the reported values were near 5%, which is reasonable with respect to what is found in the field.

5. **Actual Output Relative to the Specified Output in each Category**. For each Category test, the actual energy output expressed as a percentage of the maximum measured heat output capacity (full load) was plotted with the particulate emission rate determined for that category. The M28 OWHH categories are specified as full load (100%) for Category IV; 25-50% for Category III; 16-24% for Category II, and <15% for Category I. The particulate emissions rate values are quite sensitive to the actual energy output. Figure 2 illustrates this sensitivity for selected units and characterizes the trends observed from the data set. For most units, particulate emissions rates increase with decreasing load. In some cases, emissions rates increase exponentially in Category I and II loads. This increase is most notable and highest for units that have the highest annual emission averages. For most of the units tested, the actual test output was within the category specified in M28 OWHH. Where there was an exception, an extrapolation was made using the trends illustrated in Figure 2 for the specific unit in order to estimate the emissions rate.

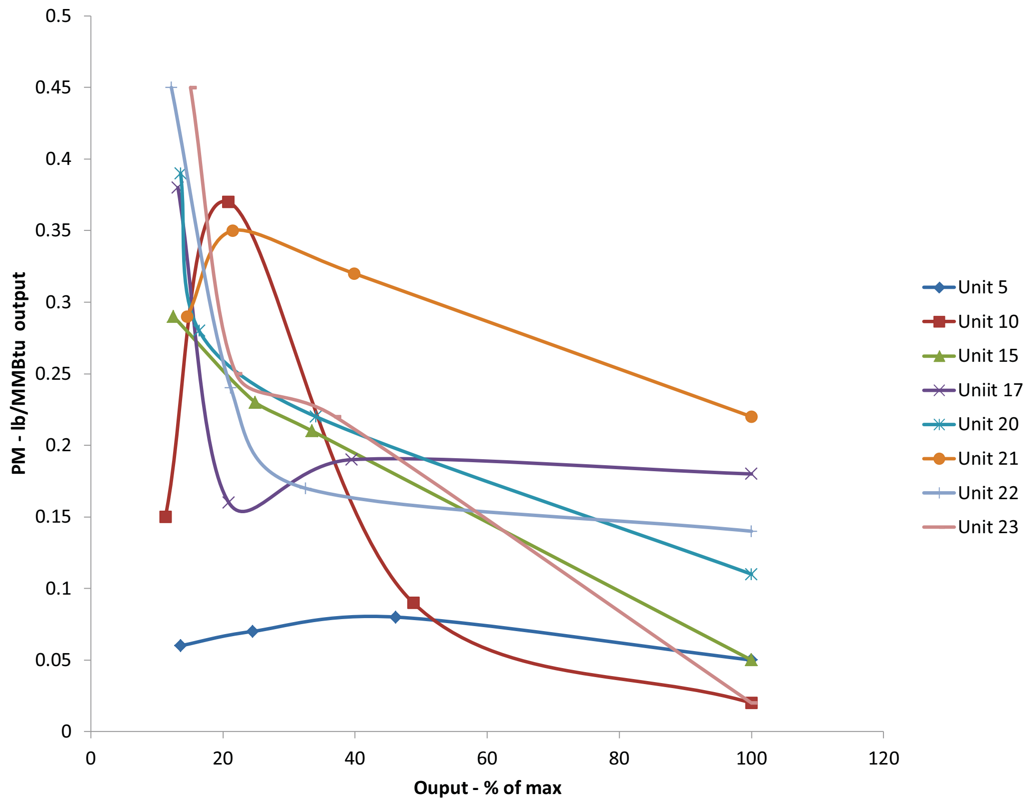

Figure 2. Illustration of reported particulate emissions vs. output for selected units. Emissions generally increase significantly with decreasing load on the heating system, even exponentially higher below 25%. Removing the lowest load from the test via substantial revisions to the test method weighting factors and load limits will greatly reduce the calculated average emissions rate for the hydronic heater, creating a situation in which the test method is even less representative of actual operating conditions.

6. **Recalculation of the Particulate Emissions Rate Based on the Load Side Output**. For all hydronic heater units, the reported particulate emissions rates were recalculated based on the output as measured on the load side. As noted above, the load side output is generally considered to be more accurate because of the higher temperature change across the heat exchanger.

4. Implementation of Review

The review was implemented by creating a test data spreadsheet for each of the 23 White Tag qualified hydronic heaters. Table 1 and 2 show an example of the analysis done for one hydronic heater unit (not identified). In the first section, “Inputs”, the relevant data extracted from the test report is summarized. In section 2 the calculations associated with the basic review are implemented. Section 3 included color coded “flags” that indicate one or more areas of the review show cause for concern. A red flag is a higher level of concern than a yellow flag. No color indicates that the evaluated parameter is acceptable. Section 4 (Table 2) shows the comparison of a recalculation of average efficiencies (annual and Cat IV) and particulate emissions rate based on the load side energy output with the values originally reported and also the stack loss efficiency. Section 5 is the implementation of an energy output analysis comparing supply and load side energy outputs determinations for each of the M-28 OWHH categories. The average percent of full-load value and efficiency for each category are also reported. Section 6 is simply an implementation of supporting calculations on the impacts of a change in unit temperature between the start and end of the test.

Table 1. Example of a White Tag qualified hydronic heater test data spreadsheet used for this review (part 1 of 2).

			Category				
1 Inputs	symbol	units	I	II	III	IV	Description of measurement
	Ts	F	175	191.3	220.2	377	Average stack gas temperature
	EA	%	117	200	160	66	Excess air
	Tsup	F	166.9	163.5	167.2	153.7	Boiler supply temperature
	Tret	F	164.52	156.1	157.11	133.83	Boiler return temperature
	Tcw	F	83.96	69.17	63.79	57.52	Cold water
	Tcwout	F	158.08	144.45	146.7	131.56	Cooling water out of heat exchanger
	Vfls	gpm	0.277	0.541	0.659	2.199	load side cooling water flow
	Vfss	gpm	4.180	6.850	8.080	8.610	supply side flow rate
	mp	lb/MMBtu	0.29	0.23	0.21	0.05	particulate emissions
	Eff	%	42	78.2	79.4	73	efficiency
	MC	%	19.37	21.13	21.7	21.09	moisture content
	dTload		83.18				
	dTSupply	F	5.2495				
2. Calculations	dTbs	F	5.25	7.40	10.09	19.87	Average boiler side delta T
	MPEbs	%	11.52	8.76	6.96	4.52	Max error in output (boiler side)
	MPEls	%	1.10	1.16	1.10	1.18	Max error in output (load side)
	MPD	%	12.63	9.92	8.06	5.69	Max difference between boiler side and load side output
	APD	%	69.44	21.80	39.50	4.95	Actual difference between boiler side and load side output
	EffComb	%	84.24	81.28	80.84	78.29	Combustion Efficiency
3. Evaluation			5.25	7.40	10.09		High Supply Side Error
							Difference between supply side and load side output out of range
					-1.44		Low combustion efficiency
							Moisture content out of range
						133.83	Low T Return

Referring to Table 1, Section 3, row 33: red “flags” are indicated in the cells as a result of high maximum potential error on the supply side. The yellow flag represents a condition that is cause for concern but not as severe as a red flag. This high potential error is due to a low temperature change across the heat exchanger on the supply side. The numbers in these cells indicate the actual temperature change (see rows 25 and 26).

Section 3, row 34 includes red flags showing the difference between supply side and load side outputs are out of range. Here the difference between these two outputs is greater than the difference could be if the specified M28 OWHH accuracy requirements were met (see rows 28 and 29).

In Section 3, row 35 there is a yellow flag, indicating that the reported thermal efficiency (row 21) is higher than expected based on the stack loss efficiency (row 30). The yellow flag indicates the reported efficiency is higher than 2-percentage points below the stack loss efficiency but not higher than the stack loss efficiency (which would lead to a red flag).

In Section 3, row 36 there are no flags, indicating all moisture measurements were within the required range. In row 37 there is another evaluation criterion and flag set for low return water temperature. The relevant version of M28 OWHH does not include a requirement for a minimum return water temperature. This evaluation criterion was included here because of discussions of including this in the next revision of M28 OWHH. In this case a flag in this row would simply be cautionary.

In Table 2, Section 5, there is also a red flag in row 49, which indicates that this specific test was done at a load higher than the range specified in M28 OWHH.

Table 2. Example of a White Tag qualified hydronic heater test data spreadsheet used for this review (part 2 of 2).

38									
39	**4. Results Average**								
40		original	load side	Comb Eff					
41	Annual Efficiency	62.5	51.3	82.3					
42	Annual PM lb/MMBtu output	0.242	0.286						
43	Cat IV Efficiency	73	70.8	78.3					
44									
45			I	II	III	IV			
46	**5. Output Analysis**		10701	24772	39832	84065	Supply Side Output Btu/hr		
47			10212	20330	27309	81501	Load Side Output Btu/hr		
48			25479	31677	50166	115157	Input Btu/hr		
49			12.7	29.5	47.4	100.0	Cat output as % of Cat IV - Supply Side		
50			12.5	24.9	33.5	100.0	Cat output as % of Cat IV - Load Side		
51			40.1	64.2	54.4	70.8	Efficiency based on load side		
52									
53			<15	16 to 24	25 to 50	Rated	Cat % Output Range from M28		
54									
55	**6. Correction for Mass, dT**								
56			-4.93	-1.3122	0.3507	-15.2348	Unit Temp Change F	561.1	Capacity Btu/ F
57			1150	704	541	235	duration (min)		
58			10557	24709	39853	81882	Adj Supply Side Output Btu/hr		
59			10068	20267	27331	79319	Adj Load Side Output Btu/hr		
60			12.9	30.2	48.7	100.0	Cat output as % of Cat IV - Supply Side		
61			12.7	25.6	34.5	100.0	Cat output as % of Cat IV - Load Side		
62			39.5	68777.3	57682.3	79318.7	Efficiency based on load side		
63			-1.4	-0.3	0.1	-2.7	% change in load side output due to mass,dT correction		
64									
65									

5 Findings of the Review

The review identified significant errors in some of the data, with the most common as follows:

- Incomplete data
- Reported efficiency values were higher than possible based on the stack loss method (one unit reported efficiency levels over 100% in several categories)
- High error in the energy output due to a low temperature differential across the heat exchanger on the supply side
- Large difference between the energy output values determined on the supply- and load-sides of the heat exchanger indicating the tests were not done within the required precision of the method
- Tests performed outside of the load specified for the category

For the 23 White Tag qualified hydronic heater units included in the review, the results can be summarized as follows:

- Full summary sheets could only be completed for 20 hydronic heater units. Three units were missing significant data and the review could not be completed. Critical parameters such as water flow rate data on either the supply or load sides were not included, although they are required to be collected under M28 OWHH and reported as part of the Voluntary Program agreement
- For 14 of 23 hydronic heater units analyzed, the reported efficiencies were higher than the efficiency determined based on the stack loss method. Of those units, eight reported efficiency higher than the efficiency based on analysis of stack losses during the category IV tests, which are essentially full load, steady firing rate. It is thermodynamically impossible for a unit to have a reported efficiency higher than the stack loss efficiency. At full load operation the reported efficiency can approach the stack loss efficiency, however it can never be greater
- For 21 of the 23 hydronic heater units, the accuracy of the energy output measurement based on the supply side data was low, caused primarily by a low temperature change across the heat exchanger. In one case, to cite an extreme example, the temperature difference was close to 1 °F, leading to a nominal error in the output of 49%. The criterion used for a low accuracy in this analysis was a temperature difference of 10 °F or lower, leading to an error of approximately 7%
- For 15 of the 23 hydronic heater units, the difference between the supply side energy output and the load side energy output measurements exceeded the maximum possible level by more than 1-percentage point, based on the nominal precision of the method, indicating that the testing may not have been done in accordance with the test method. This maximum error calculation, as discussed above, assumes that all temperature measurements and flow rate measurements are made within the accuracy required by the method. If both supply side and load side measurements were made within these accuracy constraints, this maximum error could not be exceeded. A low supply side temperature difference here does not necessarily cause this metric to be exceeded and a concern to be raised. A small temperature difference on the supply side, which is allowed under the existing M28 OWHH, leads to a high maximum possible error level. This metric does not provide information on the specific measurements that caused the high supply side/load side difference, but rather indicates that the test does not appear to have been done within the accuracy specifications detailed in M28 OWHH

- For four of the 23 hydronic heater units, tests were conducted at an output level that is higher than the category range specified in M28 OWHH. As discussed above, this can lead to lower emission rate values. This conclusion is based on the energy output as determined from the supply-side output calculation. If the load-side energy output value is used, an additional three units can be considered out of category. The supply-side energy output value has been the nominal required metric for determining load and the load-side energy output value has been used only as a quality control check. The load side energy output value, however, is considered to be more accurate based on the higher temperature difference across the heat exchanger.
- Other issues noted in the evaluation that were allowed under the test method included low return water temperature, inconsistent aquastat settings between category tests, data recording intervals that are too large to accurately characterize performance, the use of a default heating value for the wood fuel, and moisture content determinations that were outside of the range specified by M28 OWHH.

5.1. Impacts of Sizing

The ASTM method uses M28 OWHH and CSA B-415 (Canadian Standard analogous to M28 OWHH) as a starting point and is currently undergoing revisions. In the US, there seems to be support among manufacturers to increase the category load limits and the weighting factors for higher loads similar to CSA 415. For example, the load limit for Cat I is < 30% compared to < 15% for M28 OWHH. Table 3 shows the category load limits and weighting factors for M28 OWHH and a case where substantial revisions (SR) are made. The revised weighting factors would translate to evaluating the hydronic heating units only at Cat III and Cat IV under the current M28 OWHH test. As performance typically improves under higher loads, the overall emissions and efficiency performance ratings would increase significantly. In order to illustrate the impacts of load limits and weighting factors, an analysis was performed using the data gathered in the M28 OWHH review.

Table 3. Weighting factors for M28 OWHH and a case where substantial revisions (SR) were made.

M28 OWHH			SR		
	Load	weighting factor		Load	weighting factor
Cat I	<15%	0.437	Cat I	<35%	0.5
Cat II	15-24%	0.238	Cat II	35-53%	0.4
Cat III	25-50%	0.275	Cat III	100%	0.1
Cat IV	100%	0.050			

It is necessary to discuss some of the assumptions and details behind the analysis. The data only compared load side values and ignored supply data as it is expected results are to be reported based on the load side. It was assumed a Cat I SR evaluation would be carried out very near the 35% limit, which falls virtually in the middle of a M28 OWHH Cat III test. In most cases the M28 OWHH Cat tests were carried out very near the upper limit so a M28 Cat II test was conducted near 24% load and a Cat III was conducted near 50% load. The average of these two tests is 37% and it is assumed performance at 37% is very similar to 35%. With this in mind, the performance of an SR Cat I test was considered equal to the average of a M28 OWHH Cat II and Cat III test. The SR Cat II test results were considered the same as an M28 OWHH Cat III test as the performance difference between 50 and 53% are expected to be minimal. The SR Cat III test load matched up exactly with the M28 OWHH Cat IV test so the results are expected to be the same between the two. The data for three hydronic heater units 2, 11, and 18 were incomplete so they were not included in the analysis.

In Figure 3, the impacts of the SR weighting factors on the emissions ratings are depicted. The average decrease in particulate emissions rate was 0.048 lb/MMBtu and from a relative standpoint represents an average reduction of almost 20%. In an extreme case the emissions were reduced by 68% when using SR weighting factors or approximately from 0.24 lb/MMBtu to 0.07 lb/MMBtu. In four cases emissions increased under SR.

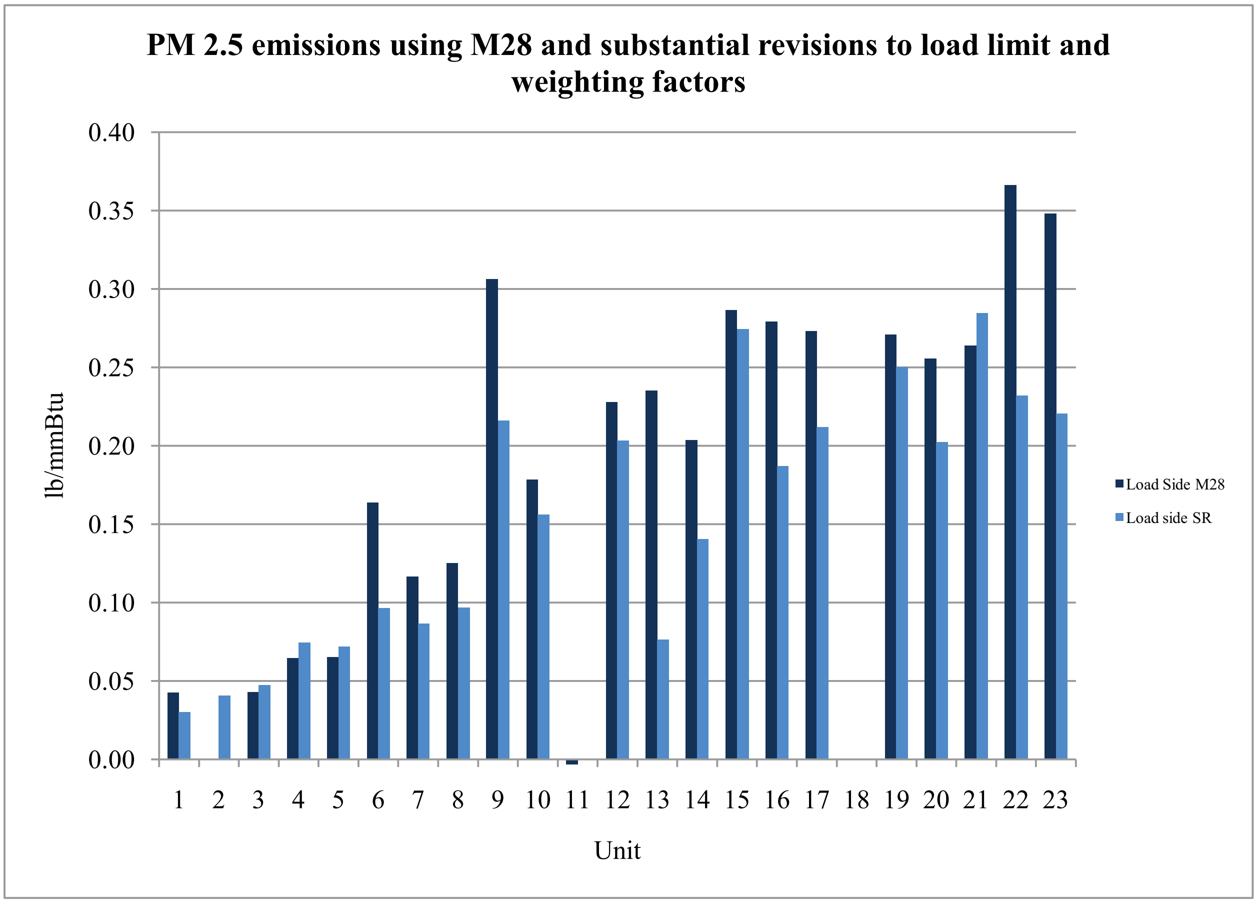

Figure 3. PM2.5 emissions using M28 and SR weighting factors. By removing the lowest load, the emissions rate using the SR parameters is reduced by an average of approximately 19%.

- Units 2, 11, 18 were not included in analysis
- Assumes Cat I of SR is the average of Cat II and Cat III of current M28
- Negative value indicates SR method increased PM
- Absolute reduction defined as M28—SR; Relative reduction defined as Absolute/M28
- Revised SR weighting factors will reduce emissions by 0.048 lb/MMBtu on average

Table 4. PM2.5 Emissions rate reduction when using SR weighting factors and load limits.

PM2.5 Reduction		
	Absolute lb/MMBtu	Relative %
average	0.048	19.2
median	0.029	22.5
min	-0.021	-15.2
max	0.159	67.6
st dev	0.051	20.8

Figure 4 depicts the impacts of the SR weighting factors on efficiency. For 17 of the hydronic heater units the efficiency increased using the SR weighting factors. The average absolute improvement was about 5.6% and the average relative improvement was about 10%. For clarification of absolute vs. relative an example follows. If a unit is rated at 50% efficiency it would be expected to jump to 56% efficiency, but the relative gain would be (56-50)/50*100 = 12%. An extreme case showed a relative increase in efficiency of 29% and an absolute increase of 15.1%. In three cases the efficiency decreased: in two cases the absolute decrease was about 2% and in the third it was about 4%.

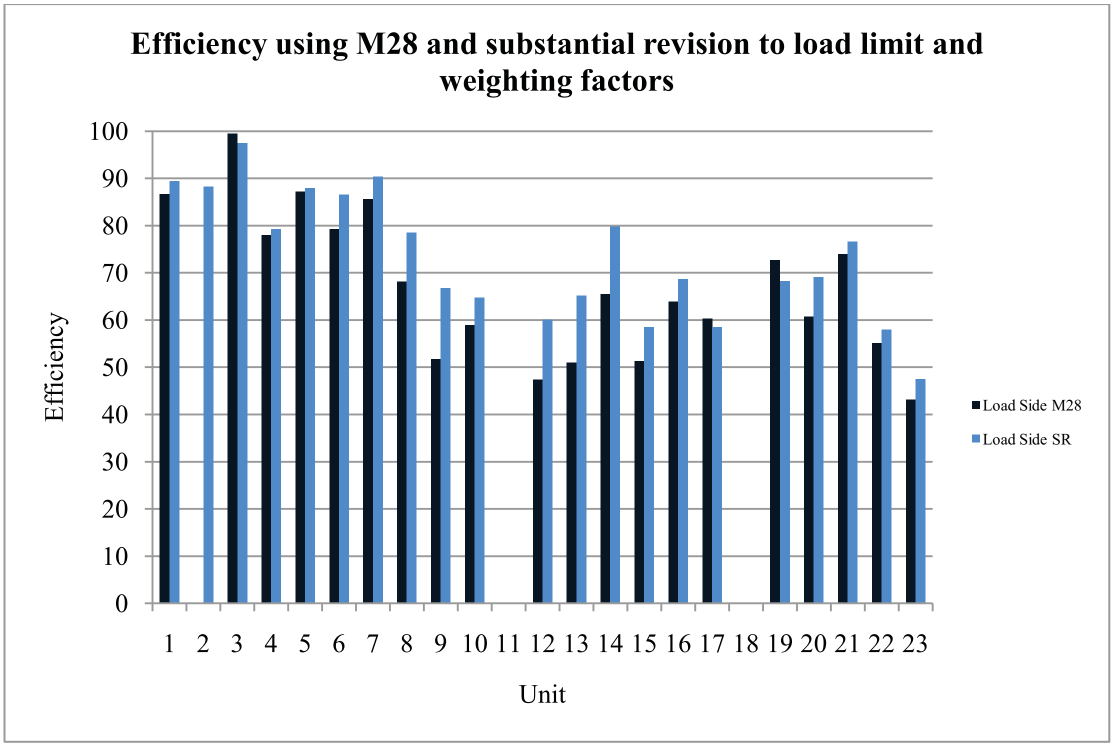

Figure 4. Efficiency using M28 and SR weighting factors. By removing the lowest load, the efficiency rating using the SR parameters is increased by an average 5.6% (absolute).

- Units 2, 11, 18 were not included in analysis
- Assumes Cat I of SR is the average of Cat II and Cat III of current M28
- Absolute efficiency improvement defined as: SR Eff - M28 Eff
- Relative efficiency improvement defined as: Absolute efficiency/M28 efficiency
- Negative value indicates SR method reduced efficiency- occurred with 3 units: 3, 17, 19
- Revised SR weighting factors will increase efficiency by 5.6% for each unit
- Efficiency improvements of >=20% (relative) in four units. Improvements of >= 10% (relative) for six additional units

Table 5. Efficiency improvements when using SR weighting factors and load limits.

Efficiency Improvements		
	Absolute %	Relative %
average	5.57	9.71
median	4.78	8.34
min	-4.43	-6.10
max	15.1	29.2
st dev	5.65	10.3

5.2. Effect of Improper Hydronic Heater Sizing on Operational Load, Efficiency and Emissions Rate

There are also concerns about the weighting factors associated with each load when sizing practices are taken into account. The design day heating load for an average home in the US is expected to be less than 65,000 Btu/hr. This value is difficult to generalize as there are a wide variety of factors that come into play associated with the local climate and design of the house. There is no doubt that there are residences with higher design day demands, for example, a large, poorly insulated home in North Dakota, but there are also several regions in which homes have significantly lower design day demands due to milder climates. In addition, the design day heating load for a specific home will be determined not just by climate but also by building design. It is also important to note that M28 OWHH is for space heating and does not account for loads such as pool heating and driveway snow melting.

Table 6 below depicts example design day heat loads based on climate. Generally speaking, North Dakota would be a very cold climate, New York would be a cold climate, and Maryland would be a moderate climate (Lstiburek, 2004). For improved performance, the heater's nominal output should be matched to the design load. As the heater's nominal output increases beyond the design day heat load, the time spent operating at lower loads increases. The average output of the White Tag units when using the load side data is 175 kBtu/hr. This leads to significant oversizing ranging from 2.7—8.8 times the design load depending on the climate. In the very cold climate this represents a maximum hourly heater output of 37% and 11% for a moderate climate. Nevertheless, the design conditions typically occur for less than two percent of the year and for 90% of the time the heating load on the building is at 70% of the design load or less (BNL, 2004). For a very cold climate, the heater output will be at or below 26% for 90% of the time, similarly for the moderate climate the output will be at or below 7% for 90% of the time. Based on the trends in figure 2, operation at these loads can lead to a substantial increase in emission rates.

Table 6. Expected loads on the hydronic heater based on climate.

	Very Cold Climate	Cold Climate	Moderate Climate
Design Day (DD) Heat load	65 kBtu/hr	40 kBtu/hr	20 kBtu/hr
Sizing factor	2.7	4.4	8.8
Hydronic heater load based on DD	37%	23%	11%
70% of DD load	46 kBtu/hr	28 kBtu/hr	13 kBtu/hr
Hydronic heater load based on 70% DD	26%	16%	7%

The domestic hot water (DHW) load for a four-member family is roughly 45 kBtu per day (ACEEE, 2011). Similar to the design day heat loads above, this is a characteristic value and can vary depending on behavior, number of occupants, and piping arrangement among other factors. When averaging throughout the day the DHW load becomes about 2 kBtu/hr or just over 1% of the average White Tag unit's nominal output. Accounting for the impacts of the DHW load variation (for example higher demand in the morning and evening, and lower demand during the day and night) throughout the day instead of evenly distributing the load is beyond the scope of this report, but it is expected to yield minimal if any performance gains considering the DHW load is very small relative to the White Tag unit's nominal output. Furthermore, operation of a hydronic heater for DHW-only production, i.e. summertime operation, without adequate thermal storage is expected to yield extremely poor performance due to this load/output mismatch.

To further illustrate the impacts of hydronic heater sizing to a home, an energy model of a code-built home located in Syracuse, NY was executed. Some characteristics of the home include R-13 walls, 2500 square feet, and a design day of -17 F corresponding to a design load of 55,000 Btu/hr. A bin-hour analysis (Figure 5) was completed on the home which identified the frequency of time spent at each load.

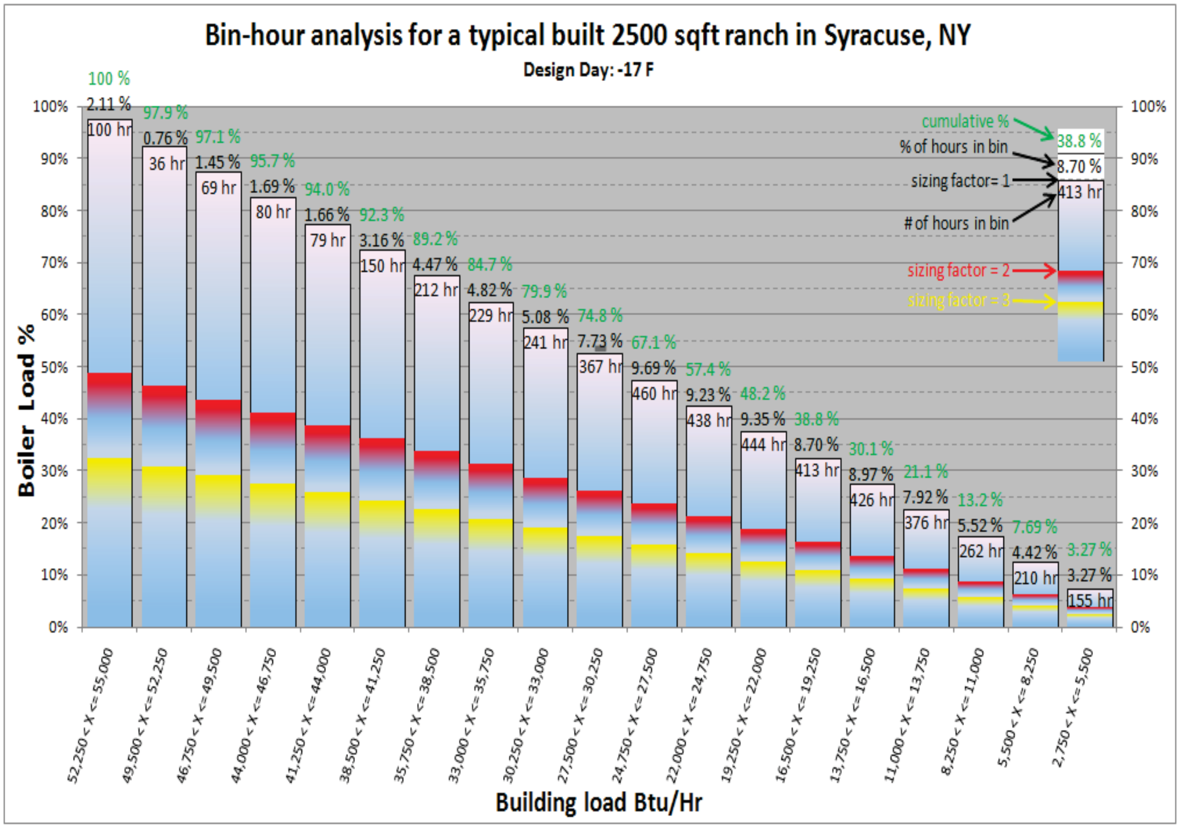

Figure 5. Bin-hour analysis for a typical built ranch in Syracuse, NY.

The loads were broken up into 5% full-load increments and it was assumed that the heat would not be turned on for loads less than 5% of the design load or less than 2,750 Btu/hr. The red and yellow bars represent the impact on hydronic heater output for sizing factors of two and three respectively. At a sizing factor of two a hydronic heater's maximum hourly output is expected to be about 50% while a sizing factor of three yields 35%. The model shows this is expected to occur for about two percent of the time. At 70% design load, the hydronic heater's hourly output is expected to be about 35% and 25% of the hydronic heater's output for sizing factors of two and three respectively. With this in mind, the average White Tag unit would be expected to operate at or below 25% output for 90% of the time.

Table 7. Weighting factors using Syracuse profile and SR revised categories

Weighting factors using Syracuse profile and SR revised categories									
Sizing Factor --->	SR	1	2	3	4	5	6	7	8
Cat I <35%	0.5	0.388	0.892	1	1	1	1	1	1
Cat II 35-53%	0.4	0.360	0.108						
Cat X 53-95%		0.231							
Cat III 95-100%	0.1	0.021							

Table 8. Weighting factors using Syracuse profile and M28 OWHH categories

Weighting factors using Syracuse profile and M28 OWHH categories									
Sizing Factor --->	M28 OWHH	1	2	3	4	5	6	7	8
cat I <15%	0.437	0.077	0.301	0.482	0.799	0.923	0.971	1.000	1.000
Cat II 15-24%	0.238	0.134	0.370	0.410	0.201	0.077	0.029		
Cat III 24-50%	0.275	0.459	0.329	0.108					
Cat X 50-95%		0.308							
Cat IV 95-100%	0.05	0.021							

Table 7 and 8 show the weighting factors of each category load for both the SR and M28 OWHH standard for the Syracuse house. A Category X is added to capture the gaps in both methods and to see where the sizing factor of an additional weighting factor would fall. The column before the sizing factor of one shows the weighting factors for both SR and M28 OWHH in Table 7 and 8 respectively. For the SR weighting factors it can be seen that the average White Tag unit, with a sizing factor of three, is fully operating in a Cat I mode.

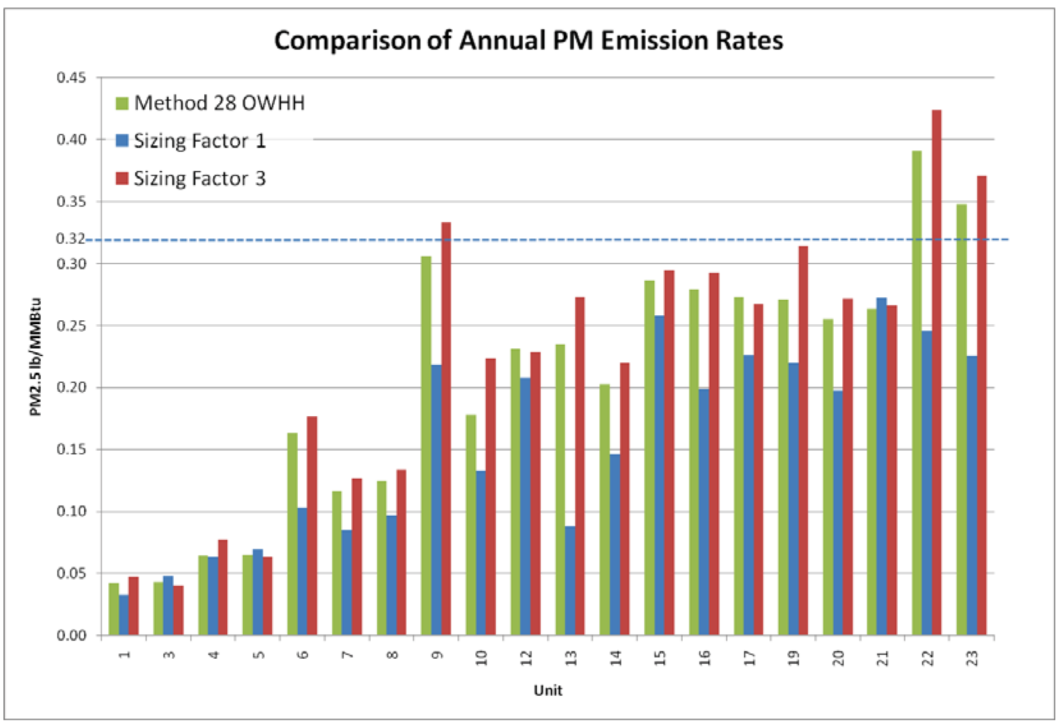

Figure 6. Comparison of emission rates based on weighting factors determined by M28 OWHH and the sizing factors with respect to the Syracuse bin hour analysis. As the sizing factor is increased the emissions tend to increase, sometimes substantially. The blue columns show that sizing to the design day heat load can yield significant reductions in emissions.

Figure 6 shows a comparison of annual PM2.5 emission rates based on weighting factors from M28 OWHH and those determined from the Syracuse bin hour analysis. The emissions for Cat X, at loads of 50-95% were approximated by taking the average of the Cat III and IV emission rates as Figure 2 shows a linear change in

emission rates between these two loads for most units. Sizing the hydronic heater to the design day heat load reduces the emission rate by about 25% on average. A sizing factor of three yields an emission rate about 7% higher on average than predicted by M28 OWHH. Although the weighting factors were determined for Syracuse, it can still be expected that reducing the sizing factors will carry similar emission rate reductions regardless of location.

It is recommended that any revisions to the weighting factors and load limits, particularly if it supports performance ratings using higher loads, are carefully evaluated by EPA during the NSPS process as the impacts of sizing are significant. As the units are increasingly oversized, the amount of time spent in the lower loads increases and performance at these loads is typically lowest. As efficiency decreases, PM emissions increase greatly, often in an exponential manner below 25% load. The Syracuse model shows that for a reasonably harsh climate, the average output of a White Tag unit provides a sizing factor of three, which yields about 90% of the operation at a load of 25% or less. It is also important to consider that these units are installed nationwide where milder winters such as in the South could yield sizing factors much larger than three, hence pushing the hydronic heater into even lower load operation.

6 Conclusions

The technical review of the test results for the 23 White Tag qualified hydronic heater units presented here found more than 90 percent of the existing tests had questionable results for efficiency and/or particulate emissions rates or were missing data necessary for their determination. Additionally, of the units reviewed, a significant number were not conducted within the precision required under the method and some testing was conducted outside of the prescribed heat-load categories.

6.1. Energy Output and Efficiency Measurements

There are significant concerns about the efficiency measurement method and results of the M28 OWHH tests. For many of the units tested, the accuracy of the energy output value derived from water temperature and flow rate measurements on the supply side of the heat exchanger is poor, and the reported efficiency levels are considerably higher than those based on stack loss measurements. Where this occurred, the efficiency results are either very inflated or simply not thermodynamically possible. For example, for one unit in a Category IV test (steady, full load) the efficiency based on stack loss measurements is 88.11% and the reported efficiency based on the supply side output is 95.2%. For this same test the nominal maximum error on the supply side is only 4.44%. Accounting for the error provides an efficiency range with a lower bound of 90.8%, which is still greater than the stack loss efficiency and thermodynamically impossible. Given the extensive issues with existing test data and method, output and efficiency ratings based on the original M28 OWHH tests as published cannot be considered accurate or valid.

6.2. Emissions Rate Measurements

While the majority of the issues in the analysis are related to energy output and efficiency measurements, the review also found issues with emission rate measurement and reporting. The following items outline general areas of concern for the accuracy of the emission rate results in the test method:

- Load side energy output rate vs. supply energy output rate—the energy output rate directly impacts reported particulate emissions rates. Energy output rates determined using the supply-side energy output rate in M28 OWHH were too high, resulting in erroneously high efficiencies and emissions rates that were too low
- Emission factors are strongly affected by the load as a percent of full load with particulates increasing strongly as load is decreased in some units. In many cases, while there is a range of loads for each category, tests are conducted very near the upper limit of the category and in four cases tests were conducted at loads outside those prescribed by the category
- The procedure used to establish full-load rated output directly affects the load range over which the Category I, II, and III tests can be run. As discussed above, in some units the particulate emission factor is very strongly affected by actual load. For marginal units this factor can easily cause the emissions rate of a unit to incorrectly be determined above or below the emissions limit of 0.32 lb/MMBtu (output)
- Tests not conducted within precision—this also affects the output and test load as a % of max load (categorization)
- Missing data—for some of the units currently listed and approved there is simply missing data which prevents completion of a proper accuracy analysis

- Data anomalies—for some units, questions arose regarding wood fuel moisture content measurements and Btu values. EPA is considering a rigorous evaluation of the wood moisture and energy measurement method and this should be conducted.

Determining the emission rates for hydronic heaters requires accurately measuring both $PM_{2.5}$ as well as energy output. The review here supports improving the accuracy of energy output but it did not encompass $PM_{2.5}$ measurement methods. Under another review, questions arose about the wash, probes, and weights with respect to the emissions leading to concerns about the emission factors. With this in mind it may be prudent to conduct a similar review to identify areas of improvement for M28 OWHH to ensure accurate measurement of $PM_{2.5}$ and emission rates.

6.3. Impacts of Sizing

The review of the test data highlights the very strong dependency of particulate emissions rates on load. An important factor in achieving low emissions is proper matching of the heating system capacity to the actual load of the building to be heated. The common heating industry practice is to use Manual J (residential load calculation) of the Air Conditioning Contractors of America. The average White Tag unit's nominal output will provide a sizing factor of about three to nine depending on the climate and building design where the units output will be 26-7%, respectively, of nominal load for 90% of the time. Heater outputs less than about 25% are of particular concern as the trends in figure 2 show that emissions tend to increase exponentially as output decreases. The analysis on the Syracuse house showed that emissions would be expected to decrease by about 25% if a unit is properly sized to the design load. Although the analysis was done for a model house in Syracuse, NY it is expected that similar performance improvements would be expected regardless of location as a bin hour analysis will show a similar amount of time spent at each percentage of the building design load. Ultimately it is essential to carefully consider sizing practices and climate with respect to category load limits and weighting factors.

6.4. Improving the Accuracy of M28 OWHH

Modifications to the existing test method are recommended to significantly improve the measurement of energy output, efficiency, and particulate emissions rate based on the findings in this review of 23 qualified White Tag hydronic heaters. They include:

- Use the water temperature and flow rates from the load side of the heat exchanger for energy output measurements. The error associated with the precision of the instruments is drastically improved (reduced) due to lower flows and higher temperature differences across the heat exchanger
- Integrate overall efficiency calculations based on the CSA B-415 Stack Loss Method as a quality control check on efficiency ratings. An input/output method for annual efficiency based on M28 OWHH load side measurements should still be the primary method
- Revise measurement and calculation methods for wood fuel moisture. Ensure the moisture content of the wood is accurately recorded by increasing the number and locations of measurements. EPA is considering a rigorous evaluation of the wood moisture and energy measurement method as part of the New Source Performance Standard
- Specify the hydronic heater temperature range to avoid possible condensing conditions which become a concern at temperatures less than 130 °F. Condensing will improve efficiency ratings for the test, however, if the hydronic heater is not designed for condensing but operated under such conditions, it will fail prematurely due to corrosion within the hydronic heater itself. Consider requiring typical operational settings for traditional hydronic heating systems: supply temperature 180 °F (range 160-200 °F) and return temperatures 160 °F (range 140-170 °F)

- Revise methods for temperature and flow measurements. Use a thermopile for temperature measurements to improve accuracy. Place the flow meter on the input side of the load side as the temperature of the water entering the heat exchanger should be reasonably constant
- Revise the frequency for data collection from 10 minutes to < 15 seconds for values such as water temperatures, flow rates, stack temperature and gas concentration. Temperature changes of >10 degrees were observed over a ten minute period. During cycling a ten minute period may not adequately represent the peaks and valleys of the cycle. A shorter time period will allow a better output measurement.
- Ensure water density calculations are based on the temperature nearest the flow meter and that the water density is based on temperatures over the data collection period (i.e. 15 seconds) as opposed to the average for the entire test (i.e. eight hours)
- Require reporting of CO_2 data. This will help to characterize combustion performance and provide a check on efficiency values
- Require reporting of CO data. CO presents a safety concern and is particularly important for units installed indoors, which will become more common in the market and are tested under M28 WHH. Similar to CO_2, it also characterizes combustion performance.

For the revisions to M28 OWHH currently planned, it is recommended that the energy output calculations based on the supply side measurements of water temperature and flow rate be replaced with energy output determined using temperature and flow rates measured on the load side of the heat exchanger. With a greater temperature difference, the accuracy is expected to be considerably better as demonstrated in this report. In some prior tests, a recirculation system on the load side was used, which led to low temperature differences but high flows. Such a system decreases the accuracy and should be discouraged. In addition, flue gas CO_2 measurements and a stack loss efficiency determination, which are not currently required in M28 OWHH should be added. Incorporating these revisions is expected to provide greater accuracy and consistency with the certification tests. It is anticipated that the revised test method will be posted upon completion of new partnership agreements with EPA.

6.5. Additional Considerations for the NSPS

Looking forward to the NSPS, the applicability of the test method to the next generation technology needs to be analyzed as distinct operational differences come with the advancements. Two-stage, gasification wood hydronic heaters are common place in Europe and beginning to enter the market in the United States. These units incorporate advanced control strategies to ensure high performance. For example, the units often use a temperature sensor and oxygen sensor in the stack coupled, via a control system, to a variable speed blower that regulates combustion air in order to ensure combustion parameters are continuously optimized. In doing so, these units can achieve efficiencies near 85% and emissions on the order of 0.05 lb/MMBtu. These units are capable of maintaining similar performance levels across a wide range of outputs, typically as low as 30% and 50% outputs for pellet and splitwood fuels respectively. To ensure outputs do not drop below these levels, advanced algorithms and thermal storage are used. The advanced algorithms reduce output as the hydronic heater nears its setpoint to prevent sudden and drastic output changes that typically carry performance penalties. For example, as the water temperature approaches the setpoint the hydronic heater will gradually ramp down its output as opposed to firing at 100% and then entering an idle mode. By coupling the system to thermal storage, an artificial load is imposed on the hydronic heater allowing it to fire at a high output regardless of the building's heating load. In a sense, it functions as a thermal battery that can be charged and then drawn down as the building requires heat.

The use of the control system, oxygen and temperature sensors, and thermal storage system allow the two-stage units to operate under a different profile than their single-stage counterparts as time spent at idle and lower loads is drastically reduced. Whereas the single stage units typically operate at lower outputs, with which M28 (O)WHH attempts to capture via a cumulative weighting factor of 0.95 for outputs of less than 50%, the two-stage units when

coupled with thermal storage typically operate at higher loads for the vast majority of the time. Therefore, a serious disconnect is realized when applying M28 category loads and associated weighting factors to two-stage units coupled to thermal storage. A review of the operational profiles of these units should be conducted in order to determine appropriate load limits and weighting factors.

Since January of this year EPA has been engaged in discussions with states and industry representatives to revise test method M28 OWHH with the goal of increasing the accuracy of efficiency and particulate emissions rates measurements. Many of the changes in the new method (M28 WHH) will address the issues identified in this review.

7 References

ACEEE, 2011. "Water Heating" Accessed, August 2011. http://www.aceee.org/consumer/water-heating

Brookhaven National Lab, 2004. Hydronic Baseboard Thermal Distribution System with Outdoor Reset Control to Enable the Use of a Condensing Boiler. Report Number BNL-73314-2004-IR. Prepared by Thomas Butcher, Ph.D.

Canadian Test Method Workgroup, 2010. Performance Testing of Solid-Fuel-Burning Heating Appliances. CSA Standard B415.1-10. Mississauga, Ontario.

Lstiburek, Joseph. *Builder's Guide to Cold Climates*. Canada: Building Science Press, 2004.

NYSERDA, 2011. Environmental, Energy, Market, and Health Characterization of Wood-Fired Hydronic Heater Technologies. NYSERDA Report, to be determined. Prepared by the U.S. EPA (Brian Gullet Ph.D. et al) for NYSERDA: Albany, NY. At the time of writing, this report was going through a final review.

NYSERDA, 2010A. Stage Combustion Biomass Boilers: Linking High-Efficiency Combustion Technology to Regulatory Test Methods. NYSERDA Report 10-19. Prepared by Brookhaven National Lab (Thomas Butcher Ph.D.) and Richard Gibbs Ph.D. P.E., for NYSERDA: Albany, NY (August). http://www.nyserda.org/publications/10_19_staged_combustion_biomass_boilers_acc.pdf

NYSERDA, 2010. European Wood-Heating Technology Survey: An Overview of Combustion Principles and the Energy and Emissions Performance Characteristics of Commercially Available Systems in Austria, Germany, Denmark, Norway, and Sweden. NYSERDA Report 10-01. Prepared by Bioenergy 2020+ (Birgit Musil-Schlaeffer) for NYSERDA: Albany, NY (April). http://www.nyserda.org/programs/Research_Development/10-01_european_wood_heating_technology_survey.pdf

U.S. EPA. 2008. EPA Hydronic Heater Program Phase 2 Partnership Agreement. Washington, D.C. http://www.epa.gov/burnwise/pdfs/owhhphase2agreement.pdf

NYSERDA, a public benefit corporation, offers objective information and analysis, innovative programs, technical expertise and funding to help New Yorkers increase energy efficiency, save money, use renewable energy, and reduce their reliance on fossil fuels. NYSERDA professionals work to protect our environment and create clean-energy jobs. NYSERDA has been developing partnerships to advance innovative energy solutions in New York since 1975.

To learn more about NYSERDA programs and funding opportunities visit www.nyserda.org.

New York State Energy Research and Development Authority

17 Columbia Circle
Albany, New York 12203-6399

toll free: 1 (866) NYSERDA
local: (518) 862-1090
fax: (518) 862-1091

info@nyserda.org
www.nyserda.org

Review of EPA Method 28 Outdoor Wood Hydronic Heater Test Results

Final Report No. 11-17
September 2011

Energy. Innovation. Solutions.