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Solid-fuel Burning Warm Air Furnace Emission Control Technology Transfer

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Introduction

This paper addresses the challenges associated with transferring emissions control technology from other appliance categories to wood-burning Warm Air Furnaces (WAF). The paper is comprised of four sections. Section 1 provides essential background information on WAFs, to set the stage for the discussion that follows. Section 2 addresses control options and challenges for smaller WAFs, and Sections 3 and 4 discuss the same issues for larger WAFs. Section 5 provides a summary of the paper's conclusions.

1.A. Categorization of Solid-Fuel Warm Air Furnaces by Heat Output

Warm Air Furnaces (WAF) that burn solid fuels[1] generally fall into two heating capacity categories:

The first category includes WAF's that are primarily intended to be an add-on to or otherwise supplement existing "conventional" (fossil fuel or electric) heating systems and are capable of meeting home heating demands for most of the heating season for many typically sized[2], typically insulated homes. However, during the coldest parts of the heating season, these add-on furnaces may not be capable of meeting the full heating demands of the home and must sometimes be supplemented with additional heat from the conventional heating system. In some cases, these smaller models may be adequate to meet the complete heating demands year round for smaller, well-insulated homes or in warmer climate zones. For some homeowners, add-on furnaces are used only intermittently to offset conventional heating and the generally higher attendant costs. For example, during the colder months, homeowners may only use the add-on furnace at night or on weekends when they are around to load and attend the furnace. While a woodstove may generally meet the supplemental heating needs for the intermittent user, these homeowners prefer the benefits of whole-house heating rather than space-heating and of having the heating source outside the living space. And during the shoulder seasons, (fall and early spring) when outside temperatures can fluctuate greatly on any given day, homeowners may choose to rely on conventional heating as a matter of convenience. And with some supplemental WAF models, the air controls are manually set on the furnace itself and not with a remote thermostat. These types of models often have little heat output turndown capability and that can be especially problematic during period of low heat demand.

For these reasons, add-on or supplemental WAF's generally have smaller wood loading capacities and have maximum delivered heat outputs under 65,000 Btu/h.[3] The second category

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[1] For the purposes of this discussion, only cordwood-fueled WAF's will be considered.
[2] In the range of 1500 – 1800 square feet.
[3] Because of the lack of standardized testing for determining the Manufacturer's Rated Heat Output, direct comparison of true heating capacity for various models has been somewhat unreliable. Different manufacturers have rated their products heating capacity in different ways. CSA B415.1-10 provides a means to rate all WAF for maximum delivered heat output on a consistent basis which will ultimately help the consumer when purchasing a WAF.

of WAFs includes models that have higher maximum delivered heating capacities and larger wood loading capacities than add-on models. These have manufacturer rated delivered heat outputs above 65,000Btu/h and frequently above 100,000 Btu/h.[4] These maximum heating capacities are intended to correspond with the design heating capacities that are used for sizing conventional heating systems employing ASHRAE or other standardized guidelines where home size and design and the location's degree days (among other parameters) dictate the recommended heating system capacity. In cases where the manufacturer makes conventional fuel furnaces or combination fuel models (wood/gas or wood/oil)[5], the maximum Btu/h rating is sometimes listed as Btu input which is the way conventional fuel models are rated. This rating convention ties back to the way furnaces are specified to meet whole house heating demands under all predicted heating demands. Models in this category generally require less frequent loading than add-on models because they have larger firebox capacities and can, therefore, hold more fuel in a given load and burn longer between refueling. For those homeowners that rely almost exclusively on their wood-burning WAF, this distinction is important. Like add-on models, these larger capacity models are frequently tied into the existing ducting systems that deliver warm air to the home and return cooled air back to the furnace.

1.B. Firebox Volumes/Heat Output/Dimensions

An internet search of eighteen WAF manufacturers and more than 50 models revealed a wide range of firebox volumes and rated heat output capacities. Firebox volumes ranged from less than 2 ft^3 to nearly 13 ft^3. Manufacturer's rated heat output capacities ranged from 48,000 to more than 200,000 Btu/h but as mentioned previously, some caution must be used since the manufacturers do not necessarily use the same or comparable methods to determine their advertised maximum heat output ratings. This also holds true when manufacturers specify a square foot heating capacity for their models.

The internet survey also included four models that have third party certifications to the CSA B415.1-10 WAF requirements with average PM emission ratings over their full operating ranges under 0.40 g/MJ. One easily observed trend is that that CSA B415.1-10 maximum delivered heat output ratings for these four models and also that the firebox volumes are at the low end of the distributions. The largest firebox volume for a currently CSA B415.1-10 certified model is 5.7 ft^3 and range as low as 3.4 ft^3. Many currently produced WAF models are larger than these models and have higher rated heat outputs. These trends can be seen in Figures 1 and 2 below.

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[4]See footnote 3.

[5]A number of WAF manufacturers have models that are combinations of wood and another fuel source. This includes oil, gas and electric systems. These models are a complete replacement for an existing conventional WAF. They still allow the convenience of having a conventional fuel back-up but often use less floor space than separate models for each fuel type.

Figure 1

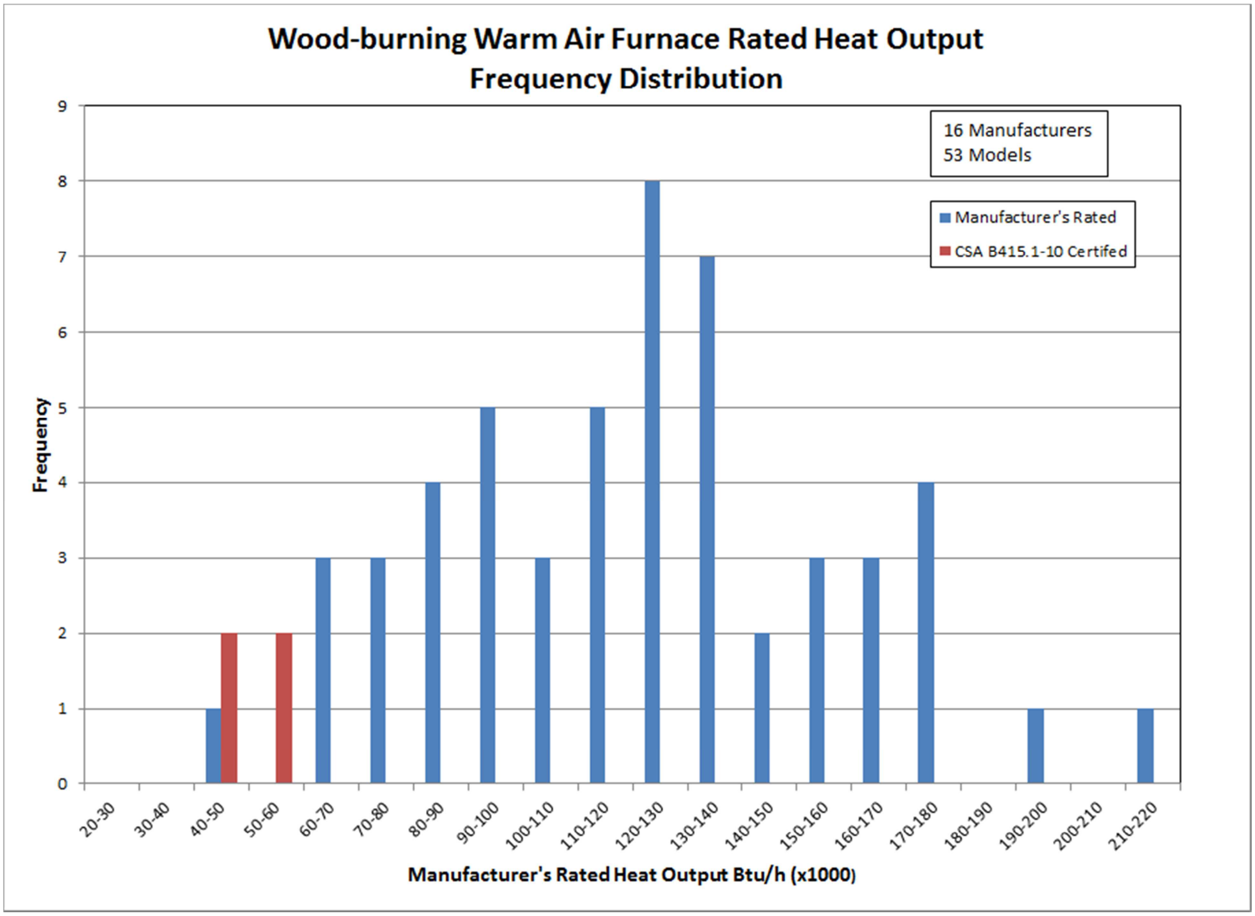
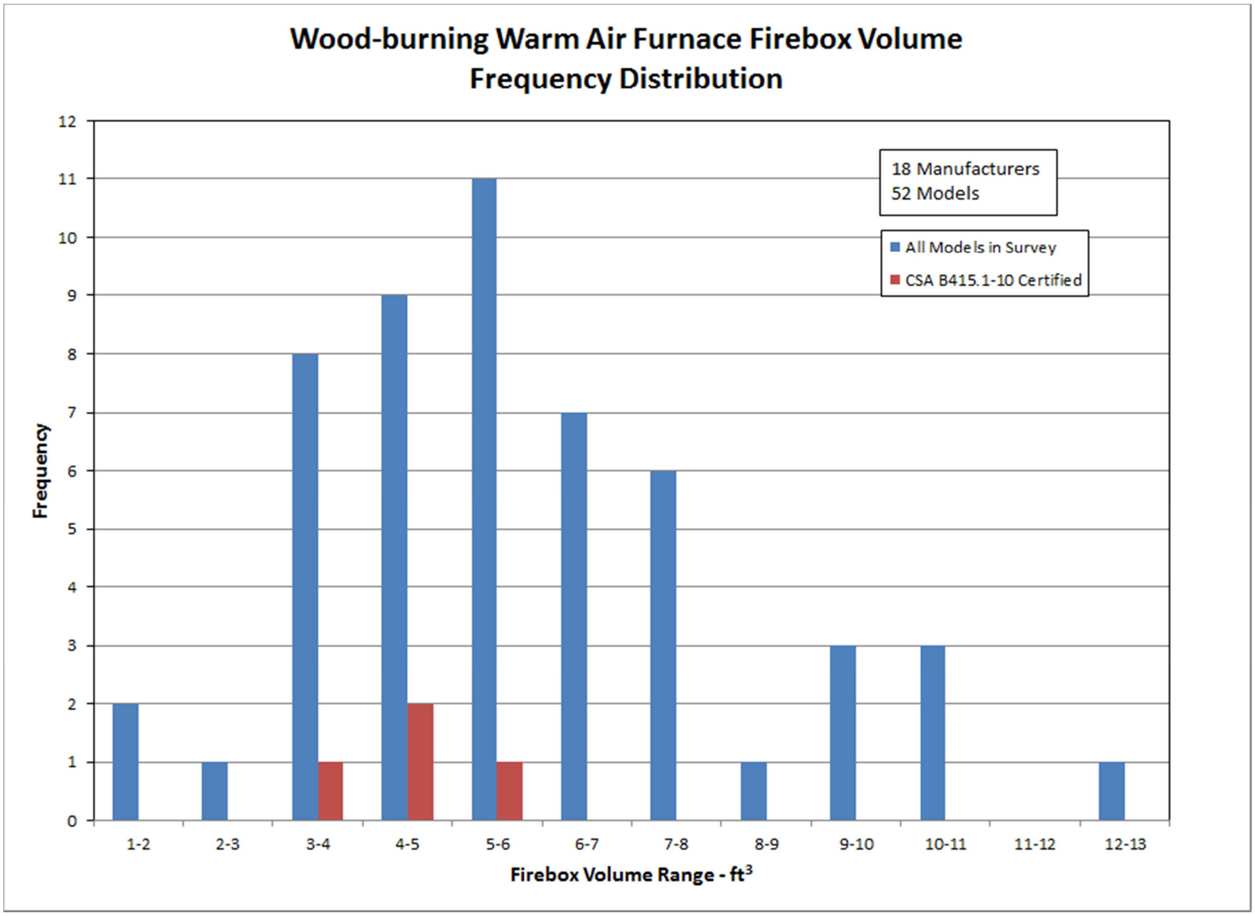

Wood-burning Warm Air Furnace Rated Heat Output
Frequency Distribution
16 Manufacturers
53 Models
Manufacturer's Rated
CSA B415.1-10 Certifed
Frequency
0
1
2
3
4
5
6
7
8
9
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
100-110
110-120
120-130
130-140
140-150
150-160
160-170
170-180
180-190
190-200
200-210
210-220
Manufacturer's Rated Heat Output Btu/h (x1000)

Figure 2



1.C. Combustion Technology Background

The wood-burning emission control development efforts for the past 30 years have been focused almost exclusively on wood-burning room or space heaters and just recently on hydronic heaters. Proven woodstove control technologies cannot necessarily be directly transferred to other wood-burning product categories, especially to the second category of WAF described above where fireboxes and fuel loads tend to be much larger than woodstoves and where the operating characteristics quite different due to the automatic control features required to maintain a set temperature in the dwelling. The basic combustion concepts, of course, remain the same, but the application of those concepts into reliable and durable product designs for whole house WAF models requires different design strategies to meet the operating challenges and homeowner expectations that are presented.

WAF models, regardless of the fuel type being utilized, are expected to maintain a near constant temperature in the dwelling without constant human intervention. A wall-mounted thermostatic control is generally the primary user interface. The homeowner simply sets the desired temperature and the thermostatic control regulates the WAF output to maintain that temperature within a few degrees. This operating paradigm becomes somewhat more complicated when burning cordwood as compared to burning fossil fuels or even particulate solid fuel like wood pellets, wood chips or coal. With cordwood- fired systems, the user has additional interfacing including fuel loading, ignition and ash removal, all done manually. In the periods of time between those fueling-related actions, the homeowner expectation is that the dwelling temperature will be automatically regulated in the same manner as a fossil fuel burning furnace.

The highly variable nature of the cordwood fuel being burned between the time the fuel is first loaded and the time when it is mostly consumed (and ready for another fuel load) in combination the varying heating requirements for a given dwelling depending on the season of the year or even the time of day exacerbates the design challenges. The WAF must have a wide operating range to satisfy the wide ranging heating demands. Consumers do not want to be too hot or too cold on any given day. A cool morning in the fall implicates a much different heating requirement than a mid-winter night. The low heating demand periods of use present the biggest challenge in terms of achieving a consistent high level of combustion efficiency and the resultant low level of particulate matter (PM) emissions, especially when combined with the need to be able to produce high levels of heat output when needed for the coldest days or when the WAF is first started in a cold dwelling.

<u>2. Emissions Control Options – Smaller WAFs</u>

Several secondary combustion design strategies have been employed to control PM emissions when burning cordwood.

The first is sometimes referred to a thermal secondary combustion technology. In this methodology, the design focuses on carefully managing the three main components of good secondary combustion – time, temperature and turbulence – the three "T"s as they are known. Critical element include: causing the volatile organic materials (combustible gases/vapors) emanating from the pyrolyzing wood in the firebox to elevate to a <u>temperature</u> where combustion of those materials will initiate; providing for good <u>turbulent</u> mixing of those combustible materials with the proper amount of fresh air needed to support combustion; and maintaining the optimum conditions for secondary combustion for the longest possible <u>time</u> to allow the most complete combustion possible, thus reducing the unburned combustible materials that comprise pollutant emissions. Because of the way wood burns, there are constant variations in the quality and temperature of the combustible materials emanating from the fuel load. This makes it difficult to consistently maintain the conditions needed for sustained secondary combustion.

In one type of design, secondary combustion is achieved at the top of the firebox where secondary air is metered into the flames above the burning fuel load in a manner that helps sustain secondary combustion. In this variation there is no secondary combustion system that is distinctly separated from the firebox. The secondary combustion features are integrated into the firebox itself. These types of systems can have interruptions in secondary combustion when conditions within the firebox change rapidly or are not close to optimum.

A second type design employs a catalytic combustor as a means of establishing and maintaining good combustion performance under less optimum conditions, most specifically when the temperature in the firebox is lower than that needed to initiate thermally induced secondary combustion. The catalytic material present on the catalytic combustor element allows secondary combustion to initiate at temperatures that are as much as 500°F lower than would otherwise be needed. These systems require a movable damper to allow combustion gases to bypass the catalytic element during start-up and refueling when the restriction caused by the catalytic element might otherwise cause smoke spillage from the load door. Generally, the bypass is closed and the catalytic element engaged only when there is a well-established fire and preheated firebox but can provide clean combustion over long period of time and under somewhat variable firebox conditions.

While both thermal and catalytic secondary combustion systems each have positive attributes, both have limitations in their application to wood-burning WAF heating systems and especially when applied to whole house heating systems where wide operating ranges, including very low to high heat output capability, are needed to fulfill the full heating demands of a typical dwelling.

The differentiation in firebox capacity and maximum delivered heat output capability are important discriminators for WAF's because they define which emission control technology opportunities can be reliably employed in WAF designs.

Woodstove emission control technology has already been applied to current CSA B415.1-10 certified WAF models. In fact, most of these products are essentially EPA certified non-catalytic woodstoves adapted with air jackets, fans and basic thermostatic and safety controls to fill the role as WAF models. Even that is not a simple as it sounds as these models have to also meet the requirements needed to obtain a furnace safety listing[6] which is appreciably different than a woodstove safety listing and implicates additional design challenges beyond emission control. These models fall into the first category of WAF previously described with limitations in heat output and firebox capacity.

In one case, a CSA B415.1-10 certified WAF is a catalytic model. This model does have a firebox volume that is larger than the largest EPA certified woodstove but also has a limited maximum delivered heat output under 50,000 Btu/h when measured using CSA B415.1-10. This heat output limitation is an artifact of the well-proven woodstove catalytic technology employed in its design, where trade-offs that limit maximum heat output have necessarily been made to insure optimum performance at medium and low heat outputs.

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[6] ANSI/UL-391 Standard for Safety for Solid-Fuel and Combination-Fuel Central and Supplementary Furnaces and/or CSA B366.1 Standard for Solid-fuel-fired Central Heating Appliances

The ability to employ well-known and proven woodstove emission control technology begins to break down when the firebox volumes, but especially when the maximum delivered heat outputs, increase to the levels that are typical of the second category of WAF. Combustion gas volume, velocity and temperature can be vastly different in large WAF models than in even the largest woodstoves or add-on/supplemental WAF models. These differences have generally not been overcome with currently employed catalytic woodstove technology.

There is always a trade-off to be made between performance and output while maintaining a functional, user friendly and durable design.

For non-catalytic technology where secondary combustion occurs in the top of the firebox in conjunction with secondary air introduced through a series of tubes or other means under an insulated baffle, there are limitations on firebox height where this type of system will simply not work when the burn rate (heat output) gets too low. The combustible gases emanating from the pyrolyzing wood near the bottom of the firebox are simply too cool to combust by the time they reach the secondary air under those low fire conditions. This height limitation restricts the application of this type of thermal secondary combustion to WAF models will smaller fireboxes.

In almost a polar opposite to thermal secondary combustion designs, where low heat output rates can be problematic, catalytic systems can have problems if the heat output rates for a given design get too high. The catalytic element presents a fairly significant flow restriction in the combustion system and for a given size catalytic element, can restrict the maximum achievable heat output. If the flow cross-section of the catalytic element is increased too much to accommodate the higher flows associated with higher heat outputs from WAF's, emission can increase at lower heat output rates. For example, during a low heat output condition, one portion of the catalytic element might be functioning properly and another portion allowing un-combusted material to pass through. If the flow area of the catalytic element is reduced to optimize performance at the lower heat output rates, it can restrict the upper heat output limit. And the catalytic element can be negatively impacted when higher heat outputs are attempted by possible exposure to temperatures that are too high for the materials used and/or chemical attack from entrained high temperature inorganic materials in the flow stream entering the catalytic element. Both can reduce the durability of the catalytic element over time. These issues limit current proven catalytic technology's application in the second category of WAF.

3. Emissions Control Technology Options – Larger WAFs

In another variation of thermal secondary combustion, a downdraft flow path is utilized where the combustible materials emanating from the pyrolyzing wood in the firebox are drawn down through the fuel and underlying charcoal bed before entering a separate secondary combustion zone. Passing the combustible materials through the charcoal bed elevates their temperature while consuming excess air present in that flow stream. Additional fresh combustion air is then carefully metered into the combustible flow stream within the secondary combustion zone to optimize the chances for sustained secondary combustion. This type of combustion system is now commonly applied to hydronic heaters meeting EPA Voluntary Program emission limits as well as many European hydronic heaters. This “downdraft” technology would seem to have a natural application to the higher heat output, large firebox WAF’s since most hydronic heater models are typically fulfilling the same whole-house, full heating season requirements.

A set of different issues enters the discussion when considering the transfer of combustion technology from hydronic heaters to warm air furnaces. And, it should be noted that many WAF manufacturers don’t produce woodstoves or hydronic heaters and therefore do not have the benefit of prior know-how with emission control technology development or implementation. They are, in essence, starting from scratch.

4.A. Surface and Heat Transfer Media Temperatures

Hydronic heaters have some distinct advantages over WAFs in terms of surface and heat transfer media temperatures. The temperature of surfaces that are exposed to adjacent combustible materials where they are sited is an example. Any combustion device, regardless of fuel has at least some hot surfaces that must be kept at a safe distance from anything combustible. Hydronic heaters generally have at least some on-board water as the heat transfer media and that water limits the maximum temperature anywhere the water is located to a very safe level in terms of overheating any nearby combustibles. For many hydronic heaters, the water jacket covers the top and some portion of the sides of the firebox. Insulated panels generally cover both the water jacket and other exposed surfaces of the unit to limit heat loss. Outdoor hydronic heaters are especially well insulated. The water jacket and heat transfer piping to and in the home (and the thermal storage, for partial and full thermal storage models) provides another benefit as well in that at least some excess heat can be absorbed by the volume of water in the system without increasing the water temperature above the boiling point or without significantly overheating the home. This is helpful during the transitions from full-on to off during the normal operating cycles in response to the home’s thermostat where there is excess heat being produced as the system re-equilibrates and where the high mass of refractory materials that typically comprise the downdraft combustion system will continue to release heat for a significant time even when in the “off” cycle. The water mass in the system provides a heat buffer.

That buffering is not readily achieved in a WAF where the air in the system has almost no heat storage capacity and where elevated air temperatures can occur quickly and can be a true liability.

WAF models are tied into the home’s heating duct system. First, there is plenum on the WAF that directs air away from the WAF heat exchanger and into the warm air delivery ducting providing heat throughout the home, usually entering each room through a series of wall or floor registers. The plenum and ducting are typically located in close proximity to wooden floor joists, subflooring, wall studs and other combustible construction materials. Registers are exposed to contact by the occupants. In order to insure safety, the safety standards cited previously for WAFs significantly limit temperatures of all air delivery components to levels that will insure that they do not pose a fire hazard under any conditions nor expose the occupants to a burn hazard. The fact that the air in the WAF heat transfer system has little capacity for storing any excess heat, especially when compared to the water in a hydronic system, creates a significant obstacle to technology transfer from hydronic heater designs. The design challenge is to manage the heat outputs during transition modes so that the temperature limits imposed by the safety standards are not exceeded. That is a significant hurdle implicates additional development costs and time and may be insurmountable for some manufacturers. Even if this challenge is ultimately overcome, other problems can remain. During the transition from on to off in reaction to the home's thermostat, the excess heat that continues to be produced as the combustion process ramps down as well as any heat stored in any refractory mass associated with the combustion system can easily cause the air in the plenum and ducting system of quickly overheat. To prevent this from creating a safety hazard, the appliance has to be designed so that the WAF controller is forced to continue to deliver what is truly unwanted heat to the home by running the air system blowers until such time as the air temperatures are reduced to safe levels. This situation can easily cause the home to overheat during each on-off cycle. This is not a scenario that promotes customer satisfaction.

4.B. Other Fire Hazards

Downdraft combustion systems produce levels of combustible gases in the firebox that at certain time border on being explosive. If the load door is opened at the wrong time, the rush of fresh air mixing with the volume of combustible gases can cause a fireball to emanate outward from the door opening. Typically the operator is protected by the load door itself and by the general upward projection of the burning gases. When this type of flame rollout event occurs in an outdoor hydronic heater, the burning gases will generally dissipate without any significant hazard. If this same situation were to occur with a downdraft WAF located inside the basement of a home, the consequences could be very different with any number of combustible materials potentially exposed to the burning gases. This situation can occur with indoor hydronic heaters as well. The addition of safety interlocks that initiate air purges before the load door can be opened has been employed in some hydronic heater models but of course implicates another design challenge and cost increase for WAF manufacturers.

4.C. Warm air Furnace Size Constraints

Most of the hydronic heater combustion technology development in North America has been done in outdoor models. The down draft design employed in most of these models has the advantage of very quickly attaining clean combustion in the transition to On cycles, but it also relies on good separation between the combustion process and heat transfer from the hot gases produced after combustion. This requires substantial size increases to accommodate a firebox, secondary combustion chamber and heat exchange surfaces. This added volume is not generally an issue for outdoor hydronic heaters since size is not a limiting factor. Even indoor hydronic heaters can be more compactly packaged than WAFs since gas-to-water heat exchange is typically more efficient than gas to air heat exchange. WAFs require more heat exchange surface area and thus more real estate in the limited volume that is available. WAFs for the most part, are installed indoors or in basements. Indoor models must be able to pass through standard size door openings and often manhandled down a flight of stairs. Any combustion technology applied to WAFs must be designed in a manner that will not violate the size restrictions that are the industry standard for central heating devices. If anything, conventional fuel furnaces have gotten smaller and easier to handle over the years. Dramatic increases in dimensions and weight of wood-burning WAFs will be considered as a negative. The average height of 50 WAF models in the internet survey was 47" and the average width was 27".

4.D. Cost Implications

EPA Voluntary Program Phase 2 qualified hydronic heater models are much more expensive to produce than their conventional counterparts and that resulted in an average 60% increase in retail cost. The few WAF models that have been certified by third party labs as meeting the CSA B415.1-10 emission limits are around twice the price of many of uncontrolled models in their category and three-times the price of some very basic models. There is a point where increases in cost to meet emission limits will drive WAF models and manufacturers out of the market. It will take significant investment, innovation and implementation time for manufacturers to find the balance between emission reduction performance and the cost that will allow them to survive in the marketplace.

5. Conclusions

Manufacturers of smaller WAF models (< 65,000 BTU total heat output) have the opportunity to apply woodstove-based technology to reduce PM emissions. Even as simple as that might appear on the surface, WAF safety standards impose requirements that put temperature limits on air jacketing and ducts to protect against fire hazards that aren't included in woodstove safety standards, and therefore must be addressed during the product development and certification processes.

While the downdraft combustion technology used to control emissions in hydronic heaters could potentially be applied to larger, higher heat output WAFs in the future, very significant design challenges would need to be met to adopt this technology to WAFs.[7] Those challenges arise from the fundamental differences in the heat exchange media: water in the one case, and air in

[7] One major WAF manufacturer commented that, despite considerable development effort, they were unsuccessful in their attempts to apply downdraft technology to their WAF designs because of the reasons cited in this report. They further noted that there are currently no WAF models being sold that employ downdraft technology.

the other. It is much easier to manage the heat spikes that are common in low emission combustion technology in hot water-based systems than hot air systems. The WAF safety standards that address the potential fire hazards created by these temperature spikes in air jacketing and hot air delivery systems reflect these differences between water and air systems, and impose a significant obstacle to transferring hydronic heater downdraft technology to WAFs. In short, this is not a simple matter of replacing water with air as the heat transfer media and being ready for market. Size constraints on WAF models and the significant cost increases implicated by employing downdraft combustion technology are other hurdles that must be addressed. And many WAF manufacturers are in the steep part of the learning curve regarding the challenges imposed in integrating emission control technology into their WAF model lines.