

Technical Addendum

Residential Clothes Dryers: A Closer Look at Energy Efficiency Test Procedures and Savings Opportunities

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I. Introduction

This document serves as the technical addendum for “Residential Clothes Dryers: A Closer Look at Energy Efficiency Test Procedures and Savings Opportunities.” A description of our testing methodology, detailed results for individual driers, and further discussion of select topics such as opportunities for making dryers more efficient and comparison of various test loads are presented here. For discussion of key findings and their implications please see the summary report.

II. Definitions

The following terms are used throughout this report:

Acronym	Definition
CFM	Cubic feet per minute
CEF	Combined Energy Factor
EF	Energy Factor
GHGs	Greenhouse gases
%RH	Percent relative humidity
RMC	Remaining moisture content
RW	Real world (referring to test loads using real world clothing)

Drying Mode	Definition
Active	The mode in which the dryer is drying clothing
After-cycle	Special function separate from the main drying cycle including “wrinkle guard” options for tumbling clothing continuously/intermittently
Delayed Start	Setting a timer to start drying clothing at a specified time
Inactive	A standby mode other than delay start mode or cycle finished mode that facilitates the activation of active mode by remote switch (including remote control), internal sensor, or timer, or provides continuous status display
Off	The mode in which negligible power is flowing from mains voltage to the dryer; this only occurs for dryers that have electromechanical controls or that have an “Off” switch
Standby	The mode reached when cycle is not in active, after-cycle, or delayed start mode and when off power was not used (or could not be used) to turn off dryer; this is only measured after automatic power down (if applicable)

III. Ecova Dryer Test Methodology

Several of the tests we ran used the 2011 Department of Energy (DOE) dryer test procedure (see: Vol. 76 No. 4, Thursday, January 6, 2011, Part III, Department of Energy; 10 CFR Part 430, “Energy Conservation Program for Consumer Products: Test Procedures for Clothes Dryers and Room Air Conditioners; Final Rule” for a detailed description of this methodology). We also ran a small number tests using the older DOE dryer test procedure for comparison. The bulk of our testing utilized our proposed test procedure. Our proposed test procedure utilizes the 2011 DOE test procedure with several key modifications described in the paragraphs below.

Instead of using DOE test cloths (which do not represent real-world clothing) we used two test loads of real-world (RW) clothing. The first test load was a smaller (5 pounds dry weight) mix of 50% synthetic and 50% cotton. This mix uses real clothing purchased from a retail store. A detailed description of the specific articles of clothing used to create this load can be found in the Appendices. This 50/50 mix was run using the dryer “permanent press” or medium heat and “normal dry” settings and had an initial RMC of 57%. The second test load we used was a larger (10 pounds dry weight) 100% cotton load. This load also utilizes real clothing purchased from a retail store. This load was run on the dryer “cotton” and “more dry” settings and had a 70% initial RMC.

Rather than running the dryers until the clothes reached a specific RMC (as the 2011 DOE test method does), we allowed the dryers to auto-terminate in a given setting. After auto termination, we weighed the test loads to determine the final RMC. We then used the difference between the initial RMC and the final RMC to calculate the amount of water that had been removed during the drying cycle. These values, combined with our measurements of the electricity and natural gas consumed during the cycle, allowed us to calculate the source energy in kWh-equivalent (kWh-e) used per pound of water removed. We also measured the time that elapsed during each auto-terminate cycle.

The kWh-e per pound of water removed values for the 50/50 RW load and the 100% cotton RW load were then averaged to represent the typical energy consumption associated with drying an average load of RW clothing. To convert from site energy to a source energy metric that accounts for losses in the natural gas and electricity supply chain the following assumptions were applied to the average site energy value:¹

- In the case of electric dryers we assume that the electric transmission and distribution system is 90% efficient and we assume an average power plant efficiency of 32% (HHV);
- In the case of natural gas dryers we assume that the natural gas transmission and distribution system is 98% efficient. We also applied the electric system efficiency

¹ During our testing we were not within DOE tolerance levels for voltage, relative humidity, natural gas supply pressure, and natural gas energy content per mass (although this was corrected for). Rinse temperature was not measured. The atmospheric pressure during testing was 0.79 atmospheres.

assumptions to the gas dryer electric loads (for spinning the drum and fan and running displays, sensors, etc).

In addition to measuring the amount of water removed and the amount of energy used to remove this water, we measured exhaust airflow, relative humidity, and temperature. We did not measure standby power draw on all dryer models.

IV. Test Load Development Discussion

The 2011 DOE test procedure uses uniform thickness, single ply test cloths that are 50% cotton and 50% polyester. Each test cloth is hemmed to 22 inches by 34 inches from 24 inches by 36 inches and weighs 0.39 pounds per square meter. There are also energy stuffer cloths that are hemmed to 10 inches by 10 inches. This type of uniform approach is often chosen in test procedures that place the greatest emphasis on repeatability of results. While repeatability is an important attribute of a test procedure, so is *applicability* – the degree to which the results of the test procedure predict actual product behavior and energy consumption. The RW clothing we used in our testing differs from the DOE test cloths in a number of ways that significantly influence drying time, performance, and overall dryer energy use:

- Most types of clothing, towels, and sheets are more likely to be 100% cotton than a 50/50 blend. 100% cotton fabrics tend to absorb and retain more moisture than 50/50 blends, requiring higher temperatures and/or longer drying times.
- While towels and sheets are two dimensional like the DOE test cloths, they tend to be much thicker, or longer and wider, or both. This makes them more challenging to dry, in part because they can roll into a ball when tumbling and leave inner surfaces not exposed directly to warm air in the dryer.
- Most types of clothing are three dimensional, featuring two outer surfaces (front and back) and at least two inner surfaces (more if they have pockets). These inner surfaces are also less likely to be exposed directly to warm air in the dryer, so are often the last to dry.
- The fabrics from which most clothing is made are thicker than the test cloths as well, retaining more moisture.

As a result, we hypothesized that dryers would require, on average, more time and energy to fully dry heterogeneous loads of real clothing than a comparable load of DOE test cloths. Such RW clothing loads would also allow greater differentiation among the measured performance of various moisture sensing systems, since some parts of the load are likely to dry more rapidly than others.

The International Electrotechnical Commission (IEC) and Australian/New Zealand test procedures have already taken a similar approach (see the Appendices for a brief comparison table of the IEC and Australian New Zealand test loads). The IEC 61121 test procedure specifies two test loads: one cotton test load and one easy-care textile test load. The AS/NZS 2442 test procedures consist of mostly cotton (~93%) mixed loads, comprised of items such as sheets, towels and pillowcases. Both test procedures have variable test load sizes that scale with a dryer's rated capacity. There is also precedence for using RW clothing of varying thicknesses (see Table 7 in the Appendices). The

Australian/New Zealand test load that is most comparable to the new DOE test load size of 8.45 lbs consists of items ranging in thickness² from 76 g/m² to 667 g/m². Furthermore, the AHAM 1992 test procedure uses the same load items as the AS NZS test load, while the AHAM 2010 test procedure uses the same load items as the IEC cotton test load. The AHAM 2010 test load has a much smaller range of cloth thickness ranging from 185 g/m² to 220 g/m².

In the first phase of our testing, we compared four different test loads of RW clothing to the DOE test cloths in two electric dryers and one gas dryer. The testing material consistency (cotton versus synthetic) was an important consideration in choosing the test loads as well as the thickness of the testing materials. Therefore, with the exception of the heavy cotton test load, we split the cotton portion of each of the other test loads between thicker and thinner cotton clothing. The four test loads we chose to evaluate are summarized in Table 1.

Table 1. Material composition of potential RW clothing test loads

Test Load	Material Composition
RW mostly synthetic	25% cotton, 75% synthetic
RW 50/50	50% cotton, 50% synthetic
RW mixed thickness cotton	100% cotton (50% thick, 50% thin)
RW thick cotton	100% cotton

Our initial findings revealed that the two cotton loads had similar RMC levels after emerging from the spin cycle of a modern clothes washer. As expected, the two partly synthetic loads had much lower initial RMCs due to the use of less absorbent materials. We chose the mixed cotton load as one of our final test loads because it is fairly representative of RW loads, and would behave similarly to the heavy cotton test load (though some articles of clothing would dry faster than others). Since previous studies have shown that consumers withhold some clothing that they fear the dryer would over dry, we assumed the mostly synthetic test load to be less realistic than the RW 50/50 test load. After examining the results of the initial tests, we selected two test loads to be utilized for all subsequent measurements: a 10 pound 100% cotton load with 68% initial RMC and a 5 pound 50% cotton and 50% synthetic load with 56% initial RMC (see Figure 1).

These initial RMCs were an average of RMCs that came out of our tested top-load washer after one rinse and spin cycle. The 50/50 load RMC agrees well with the DOE's 57.5% RMC (they use 50/50 test cloths). For the compact dryers, we recommend the same composition and initial RMC, but one load of 4 pounds of cotton and a second load of 2 pounds of 50% synthetic, 50% cotton (see the Appendices for detail on the specific items included in each test load). These two tests were

² Technically the term should be "areal density," which is the product of thickness and volume density (e.g. g/cm³), but the volume density does not vary that much in clothing, and the term "thickness" is more intuitive.

selected to measure dryer efficiency with two very different amounts of water to be removed, and also in different temperature and dryness settings. In addition to the Australian and IEC test procedures, the British test procedure provides an important precedent here, employing two different dryer loads of varying RMC and synthetic fabric fraction. The AHAM load is only used for dryer performance, not energy use.

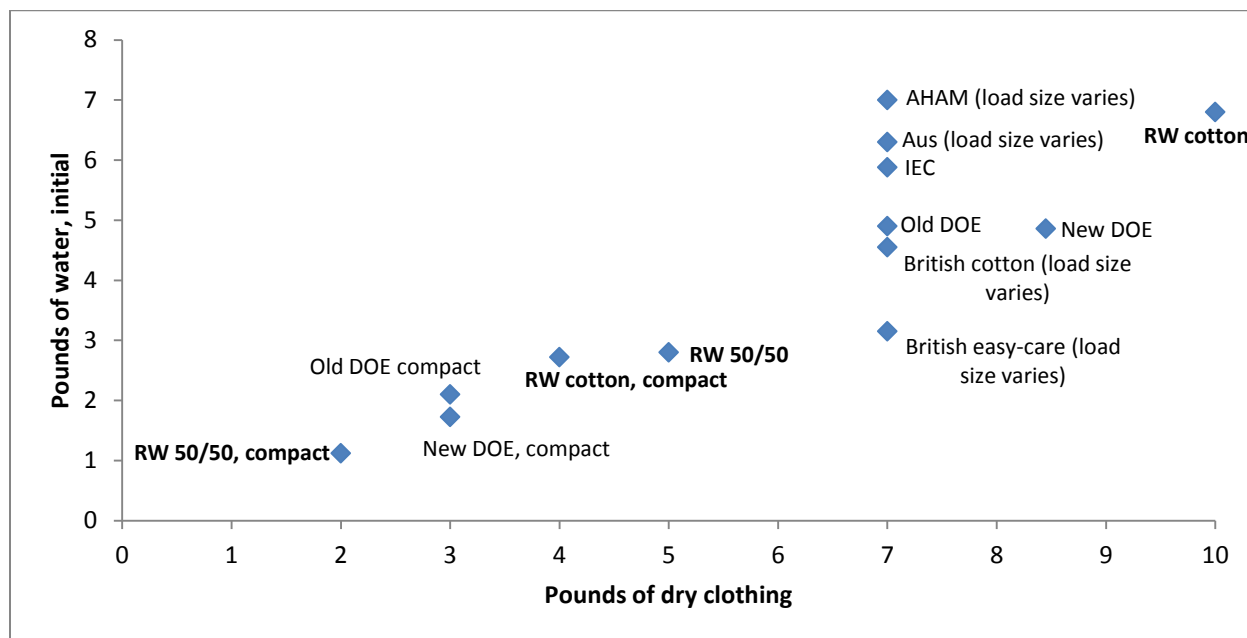


Figure 1. Pounds of water and clothing for different test procedures internationally

V. Test Procedure Development Discussion

The 2011 DOE test procedure specifies using dryers' highest temperature setting to dry the DOE test cloths. This is somewhat unusual, since most dryers and clothing manufacturers recommend using the highest temperature settings for 100% cotton loads, and a slightly lower setting for any loads containing "permanent press" or partially synthetic fabrics. As a result, we propose using the highest temperature setting for the 100% cotton load, but a medium setting for the 50% synthetic load (see Table 2).

DOE does not currently test the performance of automatic termination circuitry, and therefore specifies a final RMC to be achieved manually by the laboratory technician through repeated measurements of the clothing weight during the drying cycle. We recommend using automatic termination and the "more dry" setting for the cotton load and the "normal dryness" setting for the 50% synthetic 50% cotton load. The purpose of employing "more dry" for the cotton load is to ensure that pockets and other multi-layered portions of clothing that are difficult to dry in RW clothing do, in fact, reach levels of dryness that would satisfy users. In our initial tests, many dryers set to "normal" failed to achieve sufficient dryness in some fabric types and sizes.

Table 2. Comparison of new DOE and proposed RW test procedures

		New DOE Test Procedure (2011)	Proposed RW Test Procedure	
Test Cloths		Single-ply thin 50% cotton/ 50% polyester	(1) 50% cotton / 50% synthetic clothing with varying thicknesses	(2) 100% cotton clothing, with varying thicknesses (half thin, half thick)
Test Load	Full-size Dryer	8.45 lbs bone dry weight	(1) 5 lbs (50% cotton load) bone dry weight	(2) 10 lbs (100% cotton load) bone dry weight
	Compact Dryer	3 lbs bone dry weight	(1) 2 lbs (50% cotton load) bone dry weight	(2) 4 lbs (100% cotton load) bone dry weight
Initial RMC		57.5%±3.5% of bone dry	Moisture content resulting from the spin cycle of a typical new top load washer for each fabric type ³ :	
			(1) 56%±3.5% of bone dry	(2) 68%±3.5% of bone dry
Final RMC		3.75%±1.25% of bone dry	Automatic Termination Setting:	
			(1) Normal dryness	(2) More dry
Temperature Setting		Highest	(1) Medium (or low if medium not available)	(2) Highest
Metric for Efficiency		Combined Energy Factor (CEF)*: lbs bone dry clothing / kWh	Average source energy in kWh-e / lbs water removed (average of the two RW loads)	

*Note: The old DOE test procedure did not include measurement of “off” or “standby” modes, which are used in calculating the Combined Energy Factor (CEF). Because the 2011 DOE test procedure was only finalized only at the beginning of 2011, published data using the CEF does not yet exist. Therefore, most of this report will refer to the EF and not the CEF when discussing the DOE efficiency metric.

The settings listed above were the basis for choosing a given auto-termination cycle, even though manufacturer default settings varied among dryers (see Figure 2 and Figure 3 below). While some

³ Note that the initial RMC was similar to, but slightly lower than, DOE’s value for a 50/50 clothing load, which makes sense given its similarity to the fabric type of the DOE test cloths. However, the initial RMC is higher for the larger cotton load when spun in the same washer model, because cotton fabric tends to absorb and retain more moisture. One of the advantages of testing two different loads of clothing is to reflect these meaningful, RW differences in work load.

dryers include a simple dial with few dryer settings and a “push to start” button, many dryers try to provide consumers with lots of added options, many different drying cycles, and even a digital countdown timer, to predict when the load will finish drying.



Figure 2. Entry-level dryer with a simple mechanical dial and few cycles



Figure 3. High-end electric dryer with many choices of cycles and additional options

In the future, we believe dryers will be able to more accurately assess the level of dryness of clothing and display the time remaining before a dryer cycle is to end. There already exist some higher end dryers with this information provided on the display panel (see

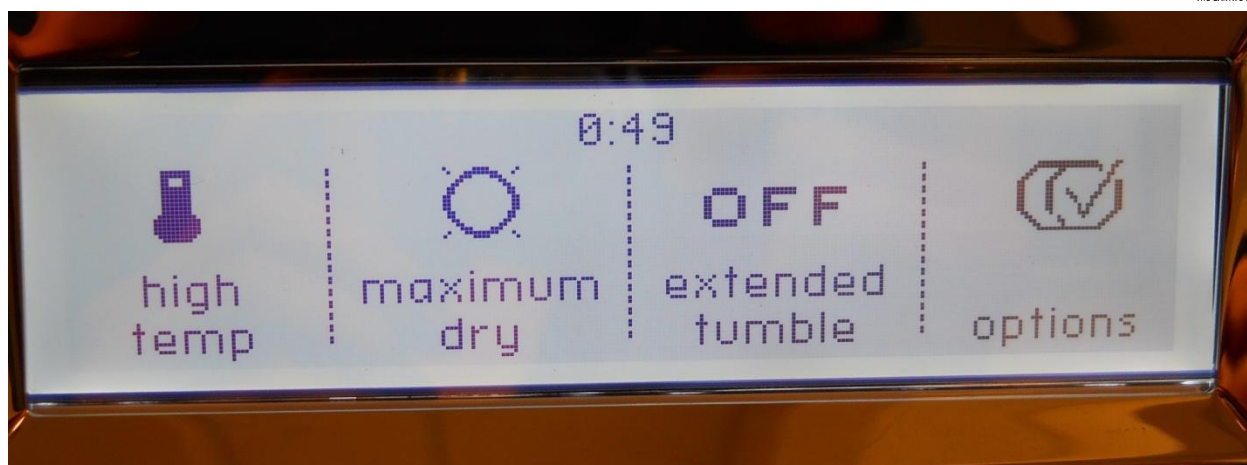


Figure 4) that varies according to the chosen program. As options and dryer settings are changed, the estimated time for drying clothing also changes. Finally, some dryers reweigh clothing after they have been loaded into the dryers as well as during the cycle to give consumers a better estimate of the time remaining.

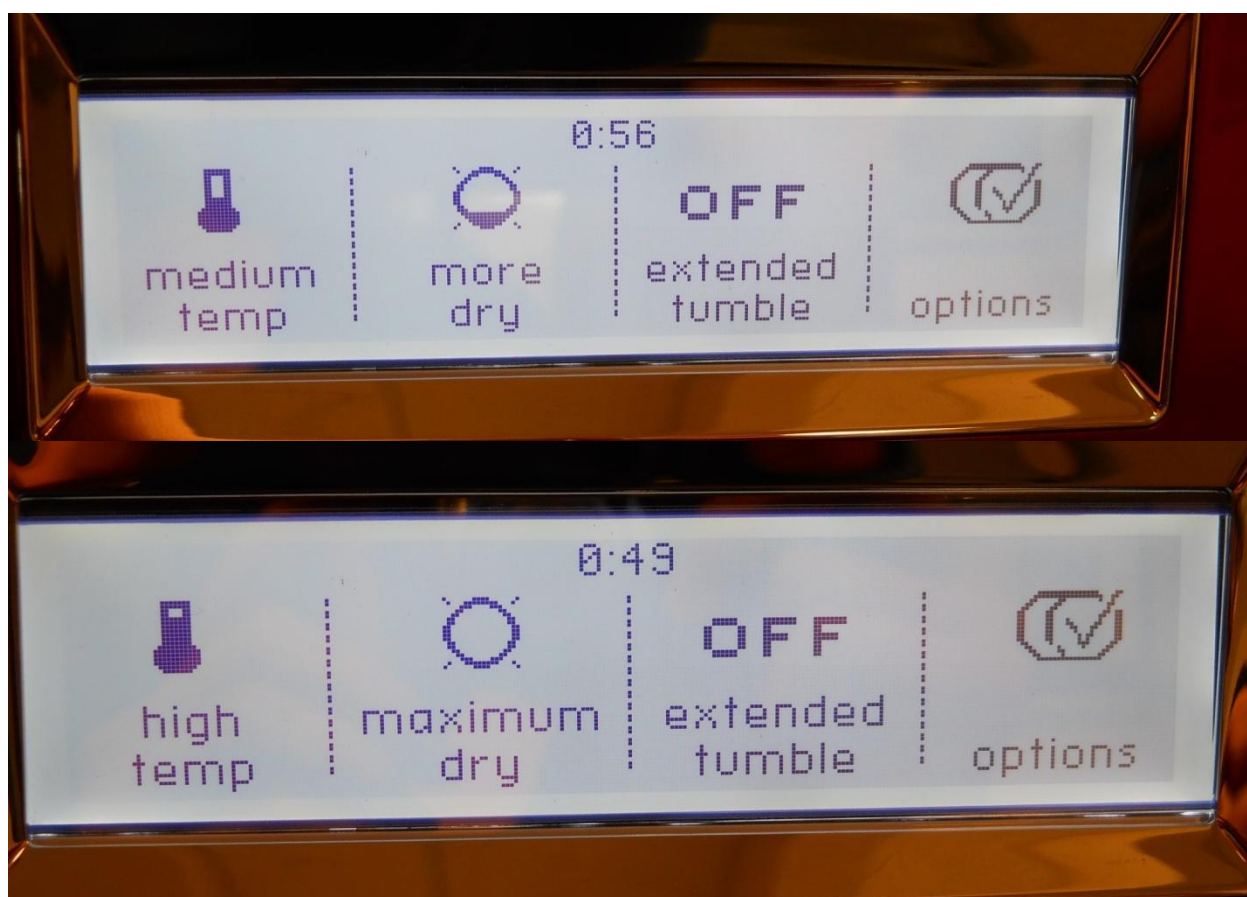


Figure 4. Two photos of a dryer display panel showing the estimated time required for two different cycles to finish drying the same load of clothing. This time displayed may also change when the actual clothing is loaded into the dryer, and during the cycle when the clothing is reweighed.

VI. Dryer Selection

Ecova conducted dryer testing using 15 different models – six gas and nine electric models (see Table 3). We purchased one model used, while the other 14 models were new. Three of the tested electric models were compact and ventless – a compact condensing unit, a washer-dryer combination unit, and a European heat pump model – while a fourth was compact and operated on 120 volts, but was vented. The only DOE dryer category not tested was compact operating on 240 volts. A number of the dryer models we tested have moisture-sensing metal strips on the stationary portion of the dryer chassis (see Figure 5), rather than on the tumbling drum itself (as is more common in European models). One model claimed high airflow, which merited testing due to its possible impacts on energy use, drying speed, and HVAC. Two other features tested include an “Eco” mode and a steam function.

Table 3. Tests performed on each dryer

Dryer Type	Old DOE Test	2011 DOE Test	Proposed Test (RW, 50/50 and 100% cotton)	“Eco” Mode	Steam Function
Electric, entry-level	X		X, X, X, X [#]		
		X	X, X		
Electric, mid-range*		X	X, X	X	
Electric, high-end*		X	X, X		
Electric, claimed high-efficiency	X		X, X, X, X [#]		
Electric, compact, 120 V	X	X	X, X		
Electric, condensing*		X	X, X		
Electric, heat pump*	X	X	X, X		
Electric, combination washer/dryer, 120 V		X	X, X		
Gas, entry-level		X	X, X		
		X	X, X		
Gas, mid-range*		X	X, X		
	X		X, X, X, X [#]	X,X	
Gas, high-end*		X	X, X		X
Gas, high airflow*		X	X, X		X

*Moisture-sensing strips present

#Four initial RW loads of varying composition and 8.45 lbs.

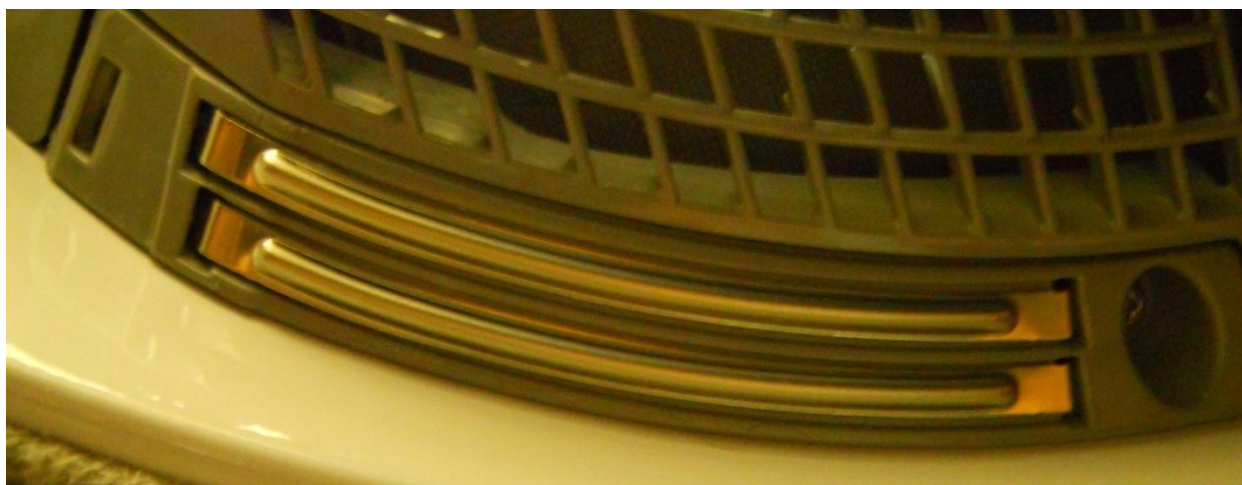


Figure 5. Moisture-sensing strips, generally located inside and below loading area

We performed a total of 58 individual tests, reflecting various permutations of dryer size, fuel type, features, test load characteristics, and temperature settings.

VII. Detailed Results

Conventional Gas and Electric Dryers

Our testing of selected dryer models included measurement of several parameters during the drying cycle. These included: electric or natural gas consumption, airflow, and exhaust air temperature. Upon termination of the drying cycle, we determined the remaining moisture content and the amount of water removed during drying.

The following four figures show time series results for typical, high-end gas and electric dryers. Figure 6 and Figure 7 show time series results for the 2011 DOE test. On each chart, the red line shows total electric power use, and the yellow line shows natural gas consumption. Airflow is indicated in green (this falls slightly over time due to clogging of the lint filter during a given drying cycle). Exhaust air temperature is indicated by the purple line. The calculated relative humidity (based on wet-bulb and dry-bulb temperatures) is light blue-gray, while the water removed is dark blue. The water removed is calculated based on the air flow and the increase in humidity of the air (see the appendices for further discussion). The agreement between the calculated and measured (weighed) water removal rates is only within a factor of two, so the water removal lines on the time series graphs are a qualitative indication of progress in the drying cycle, but not a precise one. Because an unknown fraction of the heated air leaks out of the drum at other points than through

the exhaust duct, it is not possible to precisely calculate moisture removal rates from exhaust airflow and humidity measurements.

A significant amount of information can be gleaned from the power use profiles. In this electric dryer, the heater power is approximately 4200 W, so it was able to stay on continuously during the warm-up and bulk drying stage (the stage where the exit temperature is relatively stable). The natural gas heating power (input chemical energy per time) was approximately 5500 W, so it cycles on and off even during the bulk drying stage. When the heater(s) is (are) on, the exhaust temperature increases. The electronic ignition of natural gas can be seen as a spike of the electrical power. There is also a spike in electrical power due to the motor inrush current. Furthermore, when the electrical heater turns on, its resistance is lower, and therefore draws more power, so there is an electrical spike in this case as well. When the electric heaters are off, the motor is still on, and draws approximately 200 W on the second electrical phase. Interestingly, the gas dryer takes longer to dry despite increased heater power due to the lower duty cycle leading to a reduced average temperature during the bulk drying phase, as well as the small amount of moisture released from combustion. With proper design, the natural gas dryer should be able to complete the drying process as fast as, or faster than, the comparable electric model.

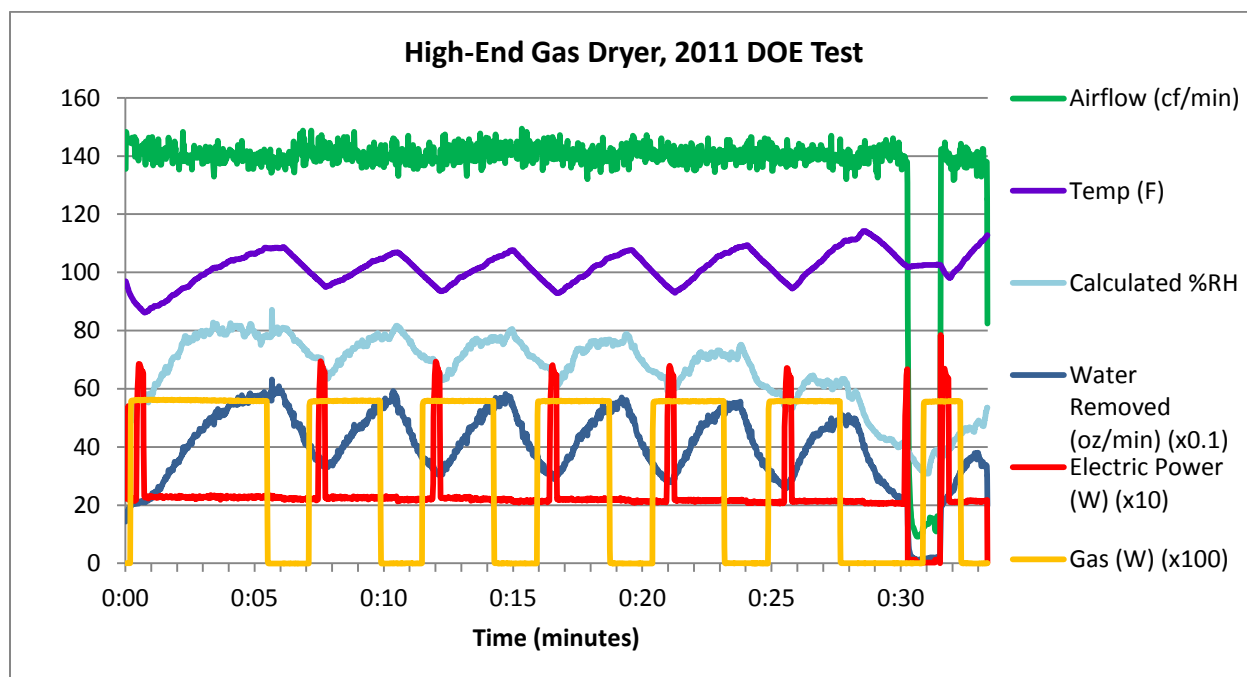


Figure 6. High-end gas dryer using 2011 DOE test, with 114 °F peak temperature, 2.64 kWh total energy use, and 3.48% RMC

Note that none of the dryers were able to gradually modulate heater power and airflow as the drying cycle progressed. As a result, the heater power turns fully on and off repeatedly in the RW clothing tests, causing exhaust temperatures, relative humidity levels, and water removal rates to fluctuate across wide ranges. In some cases, exhaust temperatures reached or exceeded 160 degrees F at peak, and would cycle between 100 and 120 degrees F before the heater switched

back on. This kind of thermal cycling can lengthen drying times and increase thermal stress on the clothing relative to the more steady heating levels seen with some dryers (Figure 7 and Figure 13).

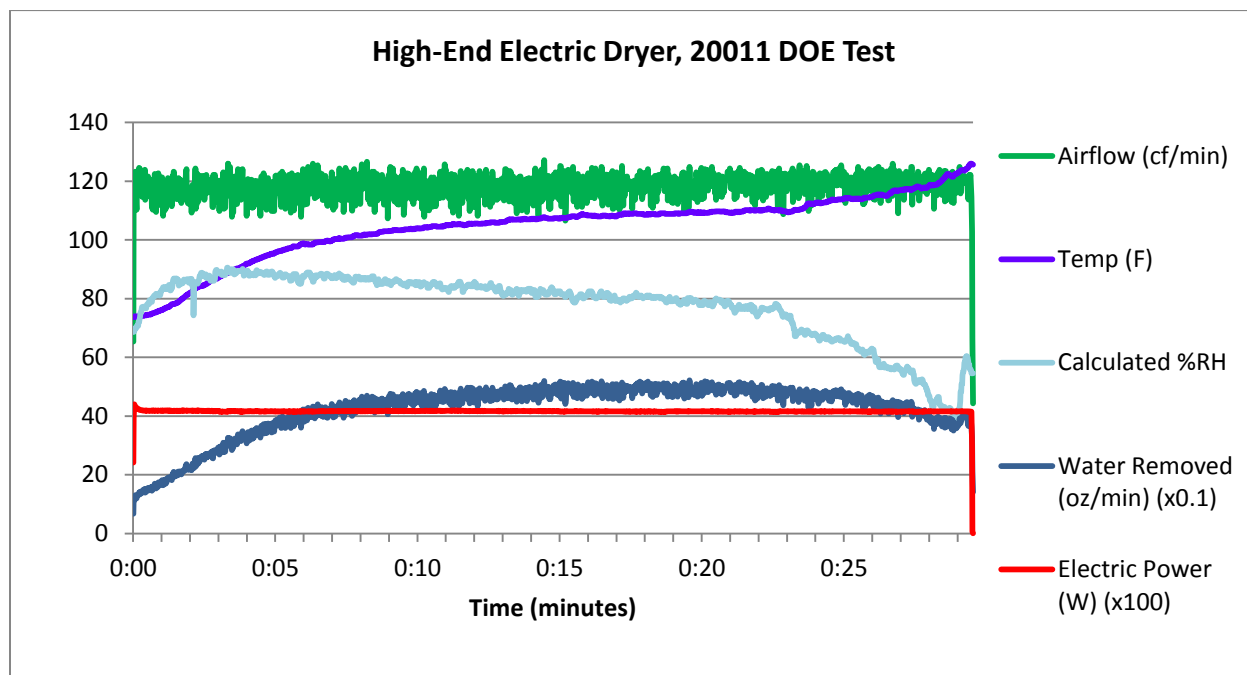


Figure 7. High-end electric dryer using 2011 DOE test, with 126 °F peak temperature, 2.60 kWh total energy use, and 3.48% RMC

Figure 8 and Figure 9 show time series graphs for RW 100% cotton tests in high-end gas and high-end electric dryers respectively. One major difference is the approximate doubling of drying time versus the new DOE test procedure, due in part to 10 pounds (versus 8.45 pounds) of dry clothing weight, higher initial RMC (68% versus 57.5%), and use of RW clothing, which requires a lower final RMC for the overlaps and pockets to be considered dry. There is a reduced duty cycle when the clothing is nearly dry, and finally there is a cool down period when the heater is off, but the fan is still on and the drum is still spinning.

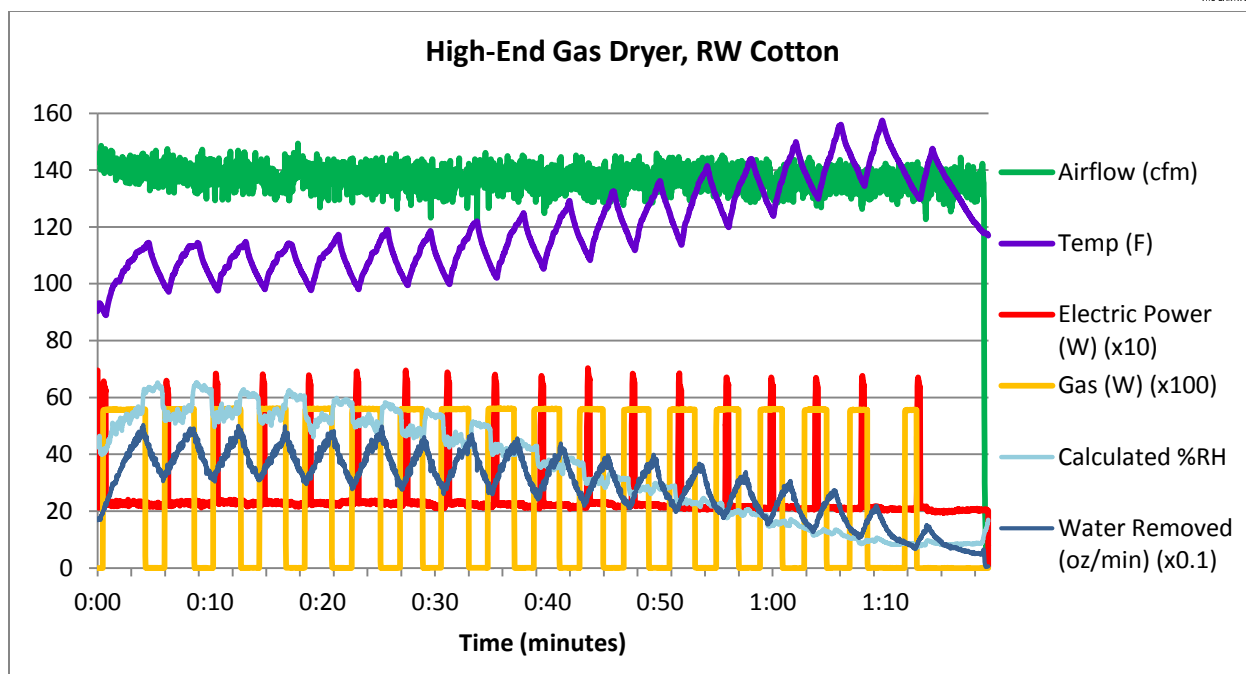


Figure 8. High-end gas dryer using RW cotton test, with 156 °F peak temperature, 3.99 kWh total energy use, and 0.60% RMC

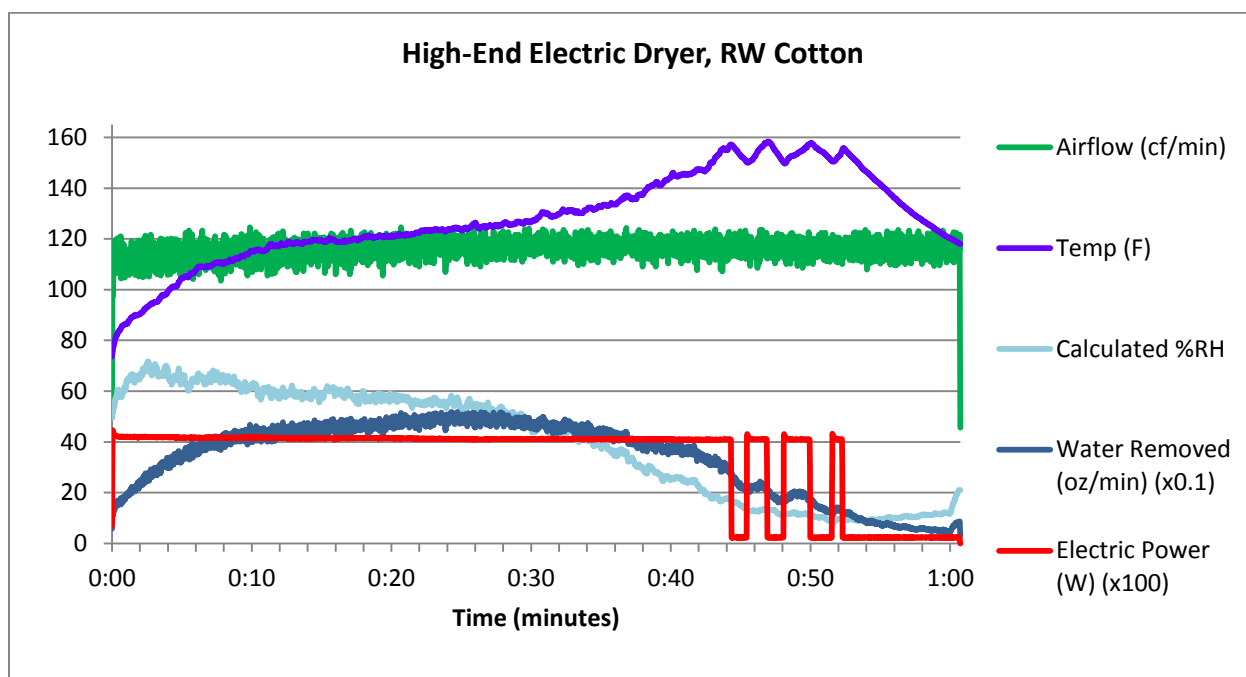


Figure 9. High-end electric dryer using RW cotton test, with 158 °F peak temperature, 3.45 kWh total energy use, and 0.40% RMC

Figure 10, Figure 11 and Figure 12 show the time series of the entry-level electric dryer with the new DOE, RW cotton, and RW 50/50 tests, respectively. For the 2011 DOE test procedure, note that power consumption drops to zero at around 21 minutes because the door had to be opened to

weigh the clothing. The airflow dropped sharply, but not all the way to zero – probably because of room air currents or natural convection. Not only does the RW cotton load take more than twice as long to dry as the RW 50/50 load, but it also reaches a much higher (20°F) maximum temperature. By comparison, even though the 2011 DOE test load consists of 65% more cloth material than the RW 50/50 test load, they have relatively similar drying times of 24 minutes and 28 minutes, as well as similar peak temperatures of 146 °F and 151 °F respectively. The drying times and energy uses are similar because the RW 50/50 goes to a final RMC of only 5.16%, while the DOE test goes to a final RMC of 2.64%. The DOE test uses the higher temperature setting, but because the cycle is terminated near 4% final RMC, it does not have a chance to get very hot. The RW 50/50 test is set to medium temperature, so this is why the maximum temperature is relatively low. It is also noteworthy that drying a RW cotton load in this dryer consumed about 80% more electricity than drying the DOE test cloths. This pattern is similar with other dryers we tested as well, underscoring the challenge of basing national energy use estimates on the energy consumed drying test cloths that are very easy to dry.

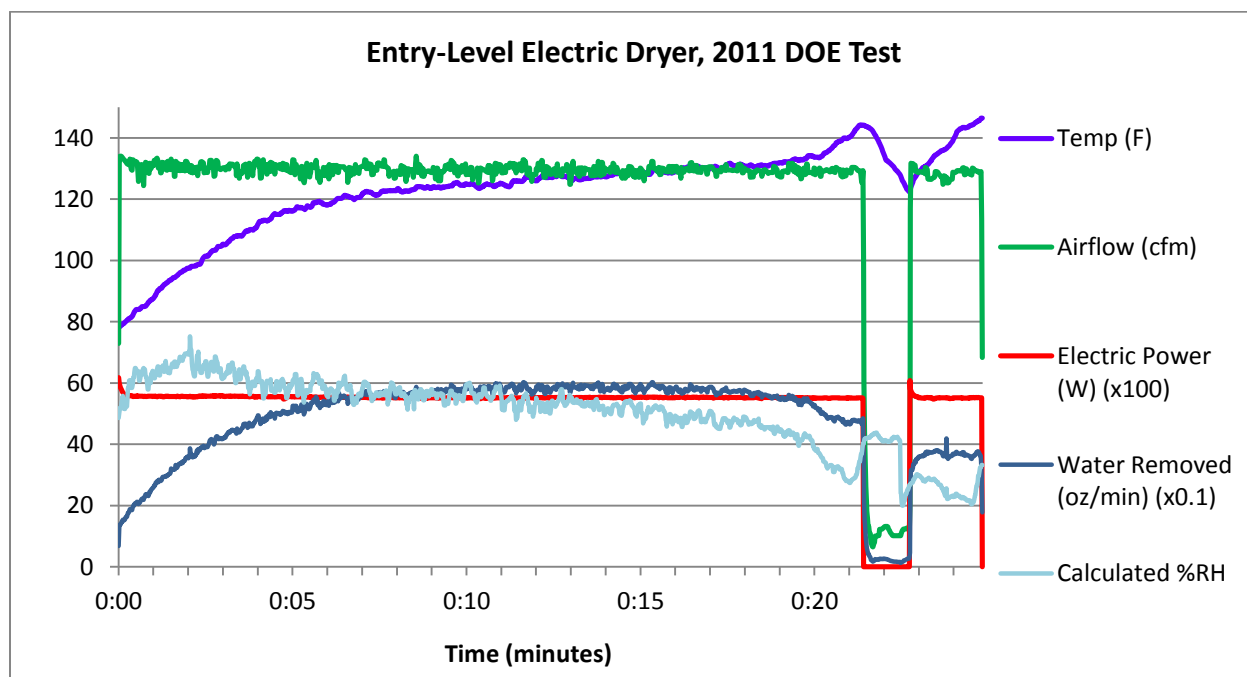


Figure 10. Entry-level electric dryer using 2011 DOE test, with 146 °F peak temperature, 2.71 kWh total energy use, and 2.64% RMC

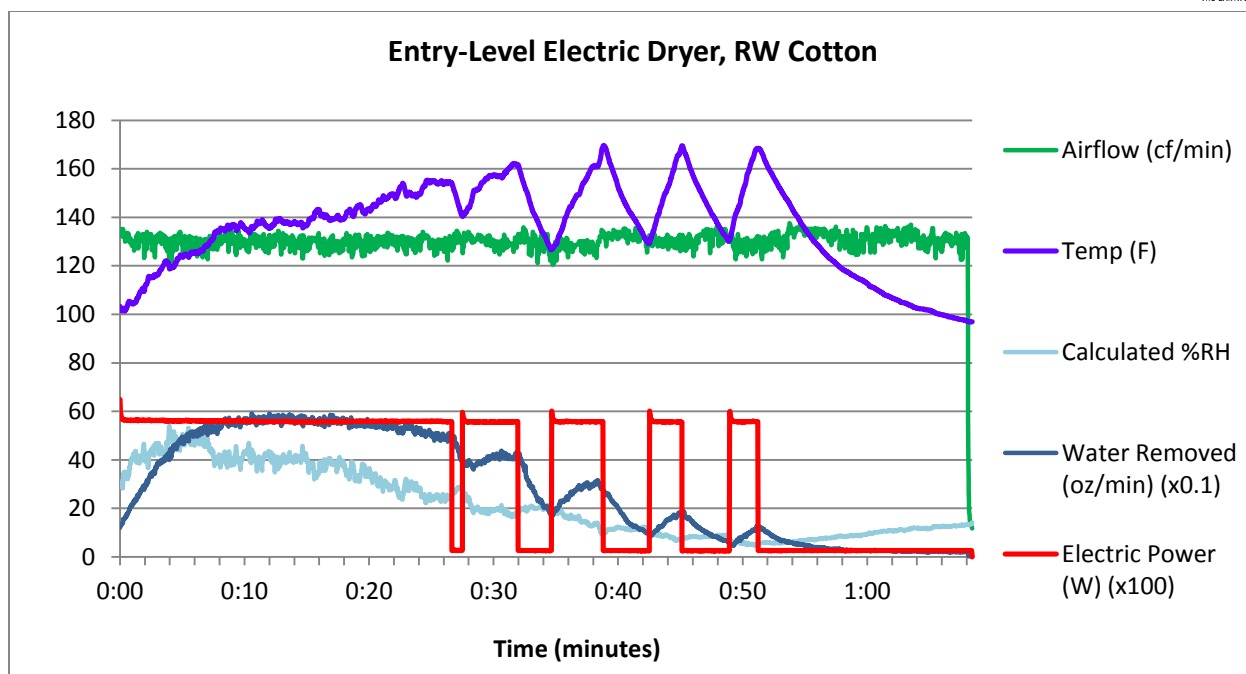


Figure 11. Entry-level electric dryer using RW 100% cotton test, with 170 °F peak temperature, 3.75 kWh total energy use, and 0.81% RMC

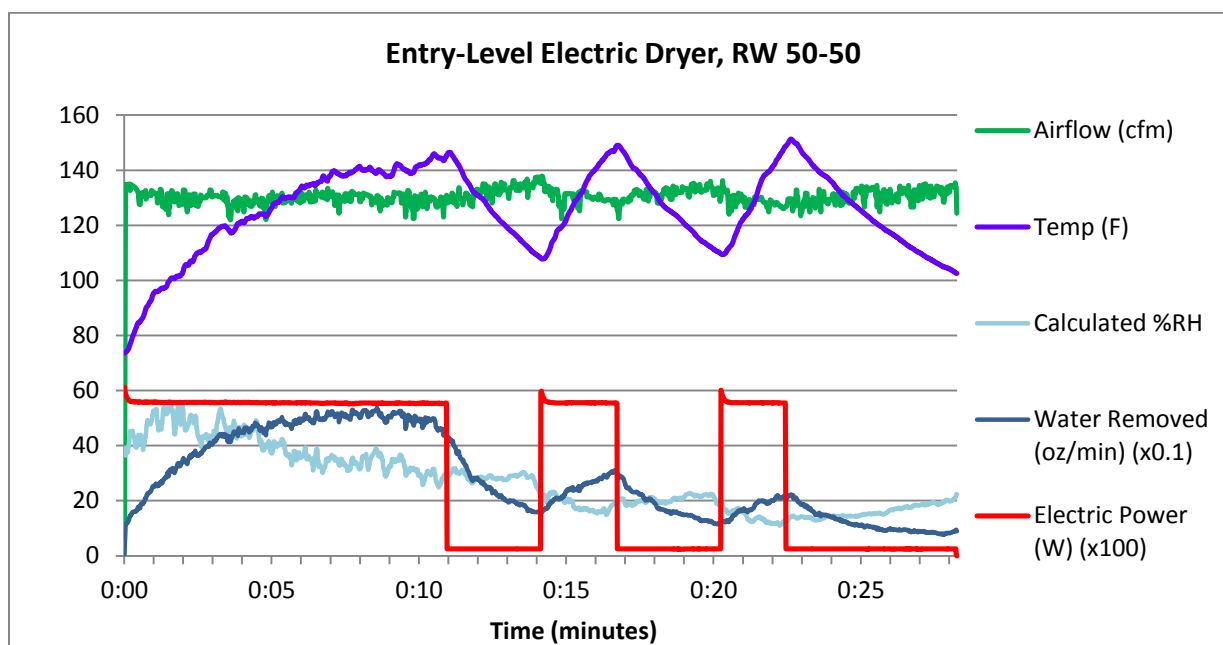


Figure 12. Entry-level electric dryer using RW 50/50 test, with 151 °F peak temperature, 2.17 kWh total energy use, and 5.16% RMC

Compact Non-Condensing (Vented) Dryers

These dryers are the same as conventional dryers, except they are smaller. Figure 13 shows the compact 120 V electric dryer with the 2011 DOE test procedure. Note the very high relative humidity of almost 90%, and the low exit temperature of about 85°F. This is because of the extremely low average flow rate of 43 CFM – less than half of what we typically see when measuring other dryers. Low air flow rates give the air time to evaporate more water and cool down to a greater extent, but, of course, also increase drying times (or reduce the amount of clothes that can be dried in a given amount of time).

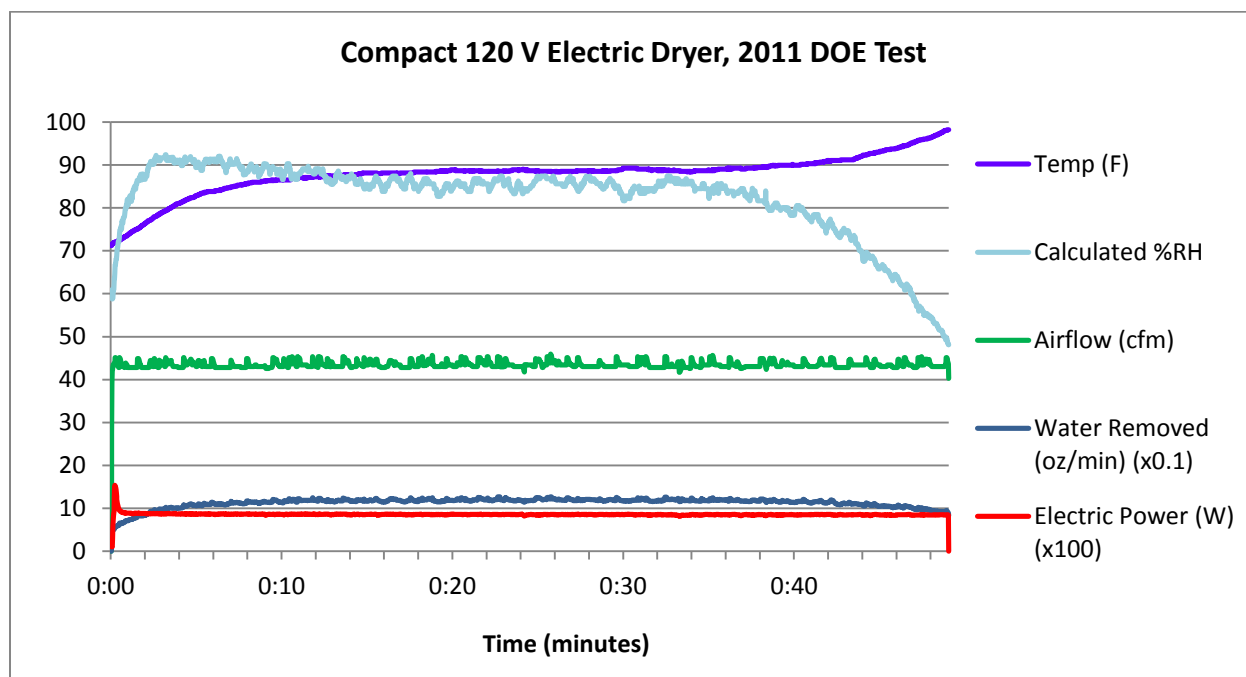


Figure 13. Compact 120 V electric dryer using 2011 DOE test, with 98 °F peak temperature, 0.89 kWh total energy use, and 3.37% RMC

Figure 14 and Figure 15 show time series results for the compact 120 V electric dryer with RW cotton and RW 50/50 respectively. Note that during the cool down period, electric power consumption is approximately 100 W, which is consistent with the lower airflow rate. Note that the airflow and water removed going to zero is an artifact of the instrument ceasing recording.

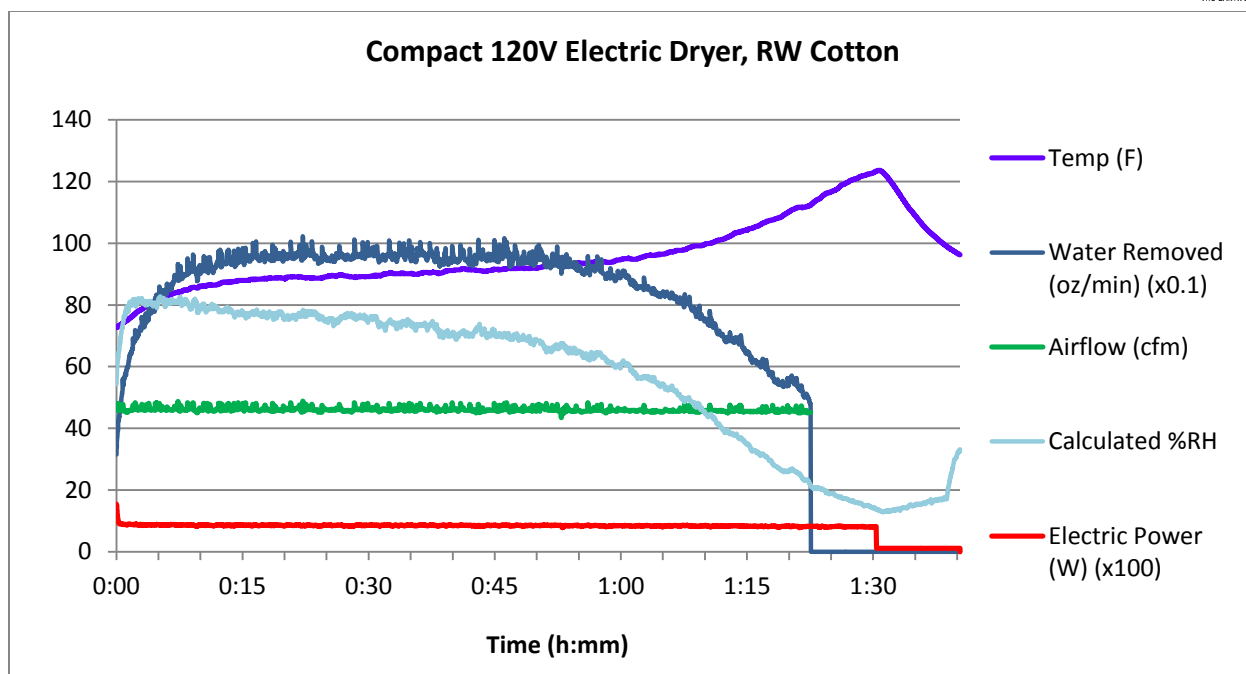


Figure 14. Compact 120 V electric dryer using RW cotton test, with 124 °F peak temperature, 1.34 kWh total energy use, and 2.26% RMC

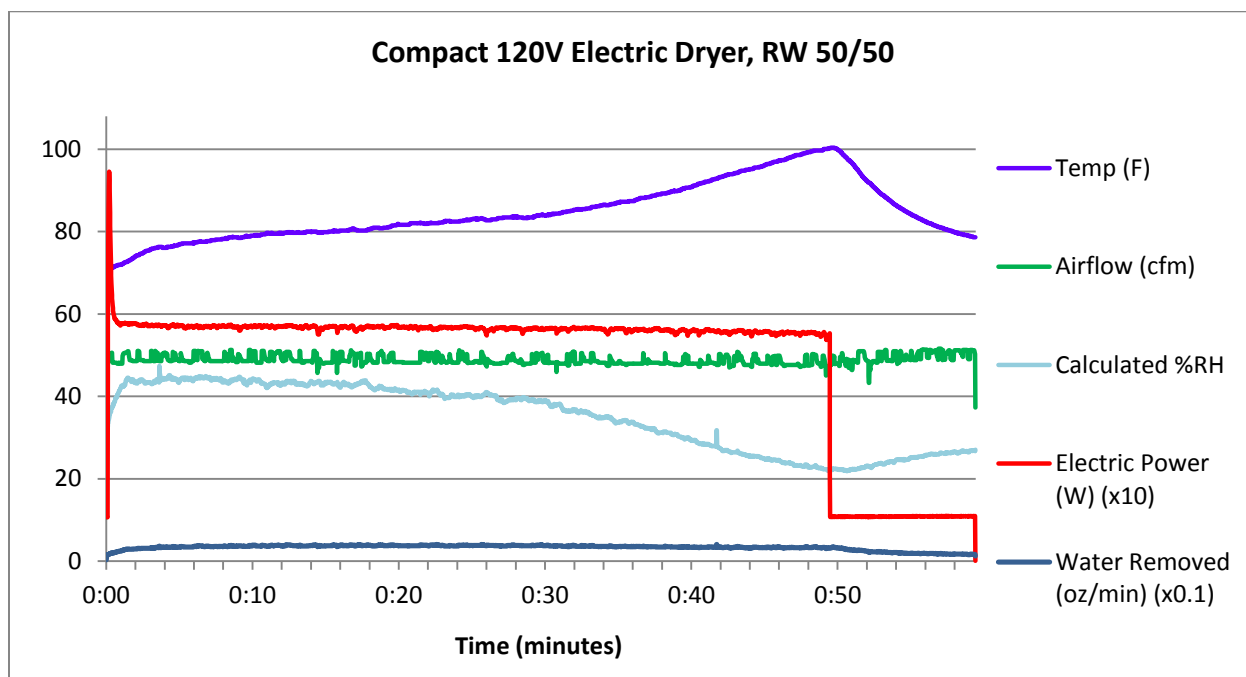


Figure 15. Compact 120 V electric dryer using RW 50/50 test, with 100 °F peak temperature, 0.67 kWh total energy use, and 5.97% RMC

None of the dryers we tested appeared to modulate heater power continuously with the need for heat. Rather they would cycle the heater fully on or fully off as needed, as opposed to having an intermediate amount of heat. However, the compact dryer – “relatively efficient” according to the California Energy Commission database⁴ – did appear to turn off one of its two heating elements during portions of the drying cycle, see Figure 16. From approximately 4 minutes to 10 minutes, the second phase heater is on, and the first phase heater is off. However, the airflow remains high. There are short periods about 15 seconds long where the airflow momentarily drops to about half, and then stabilizes at about three fourths of the normal flow (see Figure 17 for a zoomed-in view). It is possible that the drum speed is also three fourths, and there is a single motor powering both the drum and the fan, but without conducting a tear down analysis, we cannot know for sure. Regardless, because one heater stays on and one is off during this time, the heater appears to be modulating. However, to save significant energy, modulation should reduce the heater power and fan speed near the end of the cycle, which this dryer does not do consistently. The peak power consumption is only about 2.8 kW, which is consistent with a compact dryer.

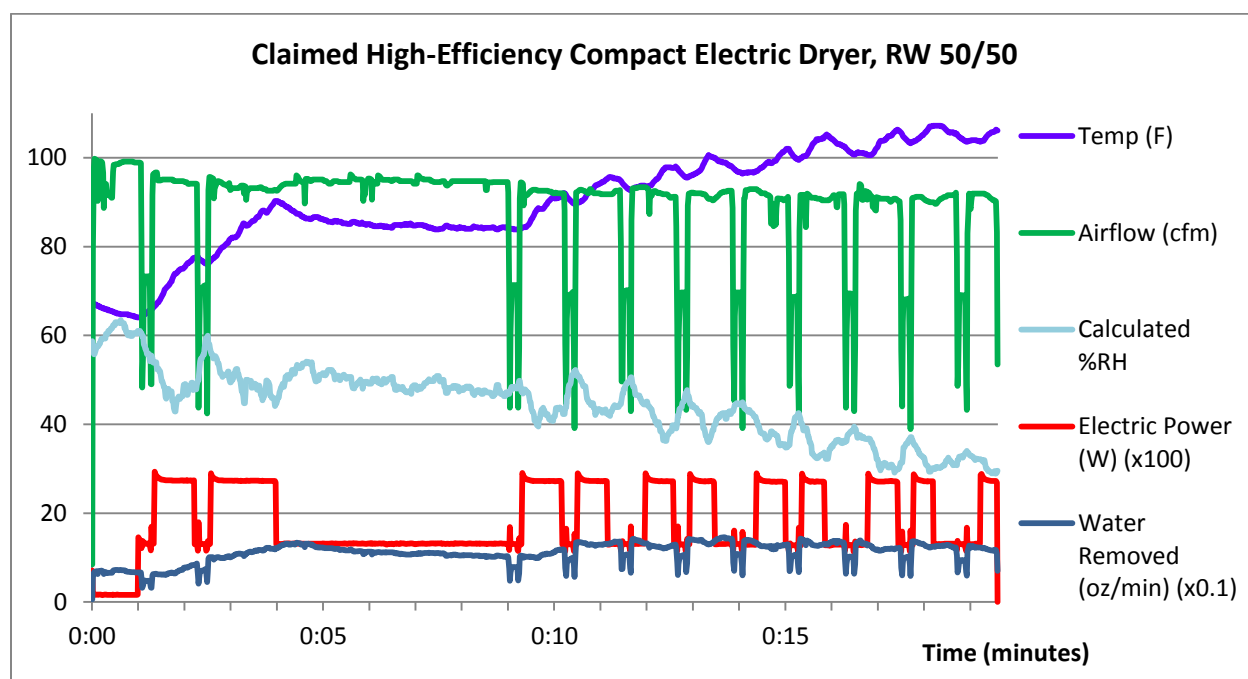


Figure 16. Claimed high-efficiency compact electric dryer using RW 50/50 test, with 107 °F peak temperature, 1.31 kWh total energy use, and 4.35% RMC

⁴ <http://www.appliances.energy.ca.gov/QuickSearch.aspx>

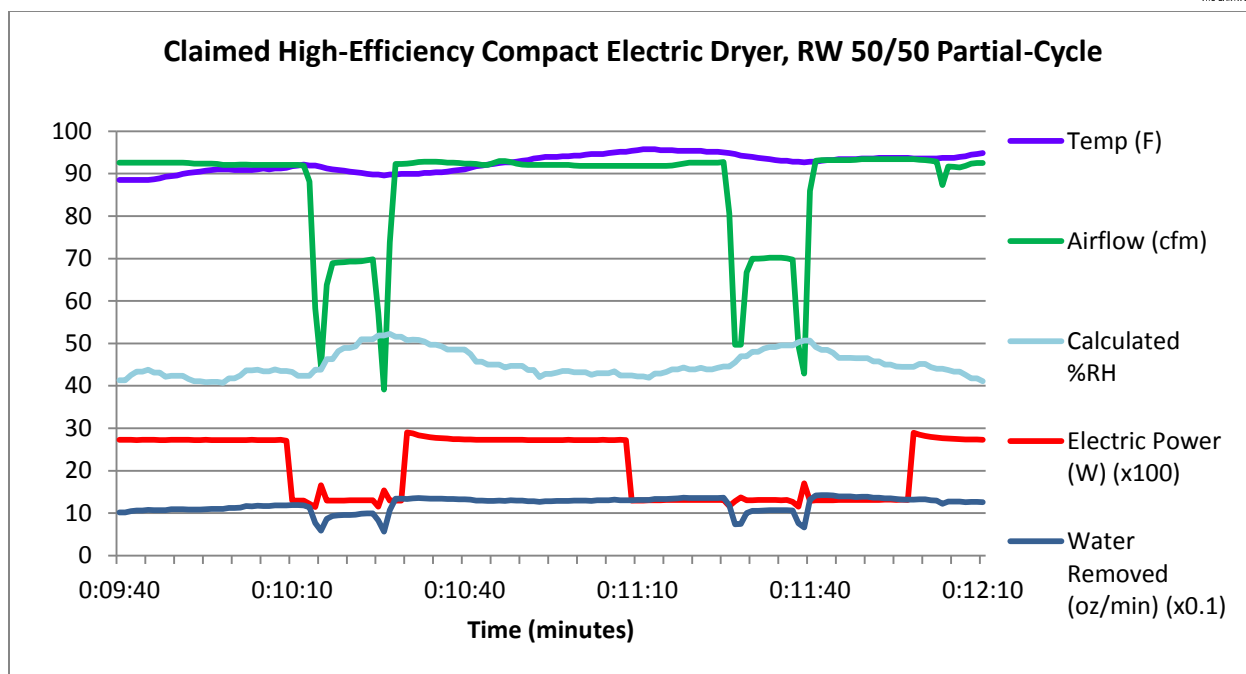


Figure 17. Zoomed-in timescale of claimed high-efficiency compact electric dryer using RW 50/50 test

Testing Steam Cycle

Over the last few years, steam cycle capability has become increasingly common on high end dryers. These features are marketed primarily for their ability to reduce wrinkles in an already dried load, or to “refresh” a load of clothing in lieu of washing and drying it. As steam cycles are not included in the energy test procedure, we tested the steam cycles of two dryers to determine the incremental resulting energy use when this feature was selected. The typical steam cycle uses approximately 0.5 kWh in the dryers we measured (see Table 4). “Wrinkle release” and “perfect tumble” are simply dryer settings associated with the steam cycle. Therefore, this feature adds approximately 20% to the energy consumption of a typical cycle. Because this feature is only available on some dryer models, is oftentimes an extra feature that is not automatically built into a regular dryer cycle and likely used infrequently, we do not believe its energy use is significant enough in total to require testing in the test procedure at this time. However, it is worth monitoring for possible inclusion at some point in the future if its prevalence increases significantly.

Table 4. Steam function energy use

Dryer	Test Load	Cycle	Dur.	Options Selected		Energy Use			
				Perfect Tumble	Wrinkle Release	Electricity (kWh)	Gas (kWh)	Total Energy (kWh)	Perfect Tumble Avg. Power (W)
Gas, high airflow	RW Cotton	Perfect Steam (High Temp)	15 min	OFF	OFF	0.0594	0.544	0.604	
	RW Cotton			ON	OFF	0.0554	0.484	0.540	
	RW Cotton			ON	ON	0.0589	0.465	0.524	187.5
	RW 50/50			OFF	OFF	0.0532	0.472	0.525	
	RW 50/50			ON	ON	0.0545	0.465	0.519	167.5
Gas, high-end	RW Cotton	Steam Cycle: Refresh	16 min	N/A	OFF	0.0642	0.509	0.573	
	RW 50/50	Steam Cycle: Wrinkle Care	20 min	N/A	OFF	0.0752	0.594	0.669	

Testing Eco Mode

In the two years since we conducted our previous research, a number of dryer models have been introduced that include an “eco” or “energy saving” mode, often prominently labeled on the control panel. We tested this feature on multiple dryers to understand whether it did, in fact, save energy when drying typical clothing loads. Figure 18 and Figure 19 show the RW cotton cycle and its corresponding eco mode cycle of a mid-range gas dryer. The peak temperatures are the same, but the main difference is that the eco mode allows the temperature to drop further before restarting the heater. Therefore, the average temperature is lower for the eco mode cycle and one would expect a noticeably longer drying time. Yet our test results indicate that the drying time only increased by 1 minute for the eco mode cycle.

The eco-mode appeared to have a larger final RMC,⁵ and this translated into about 500 Wh of energy savings, and an overall change in efficiency from 43% to 47%. This could generate 140

⁵ The final RMC without eco mode actually came up as negative, which is possible with statistical uncertainty.

kWh/yr in savings if it was always selected. These savings, however come mostly from leaving clothes less dry.

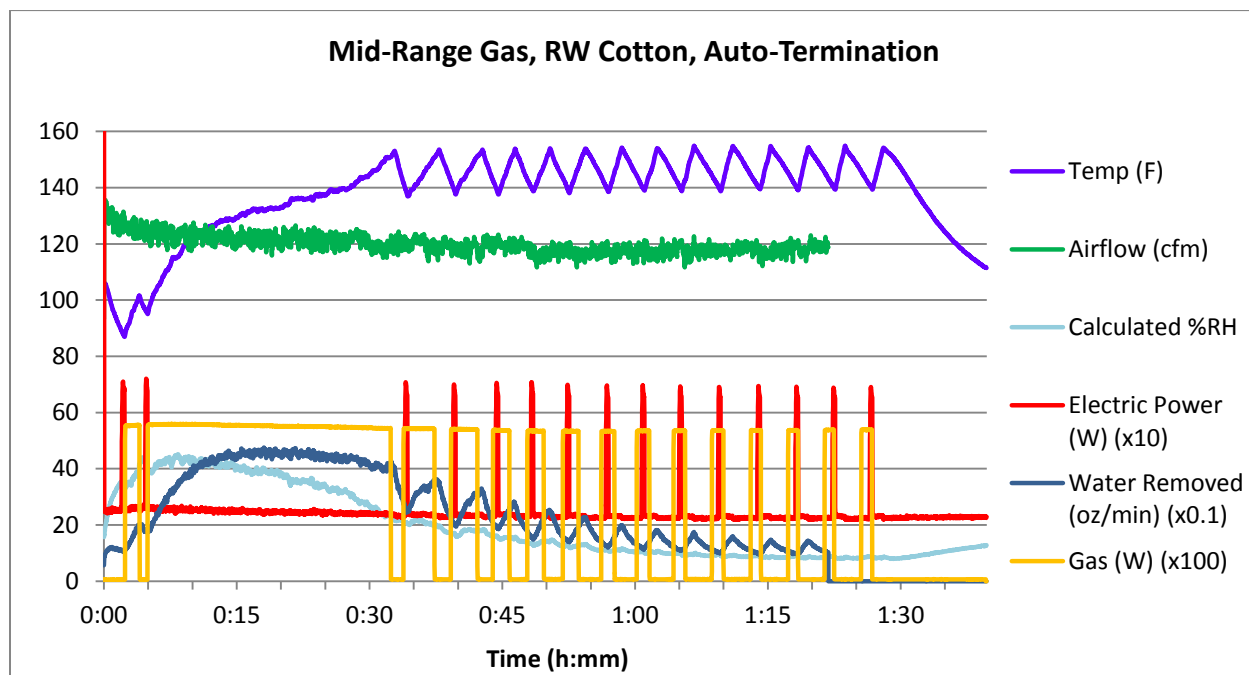


Figure 18. Mid-range gas dryer using RW cotton test and auto-termination, with 155 °F peak temperature, 4.93 kWh total energy use, and 0.0% RMC. Note the airflow meter stopped recording at ~1:20

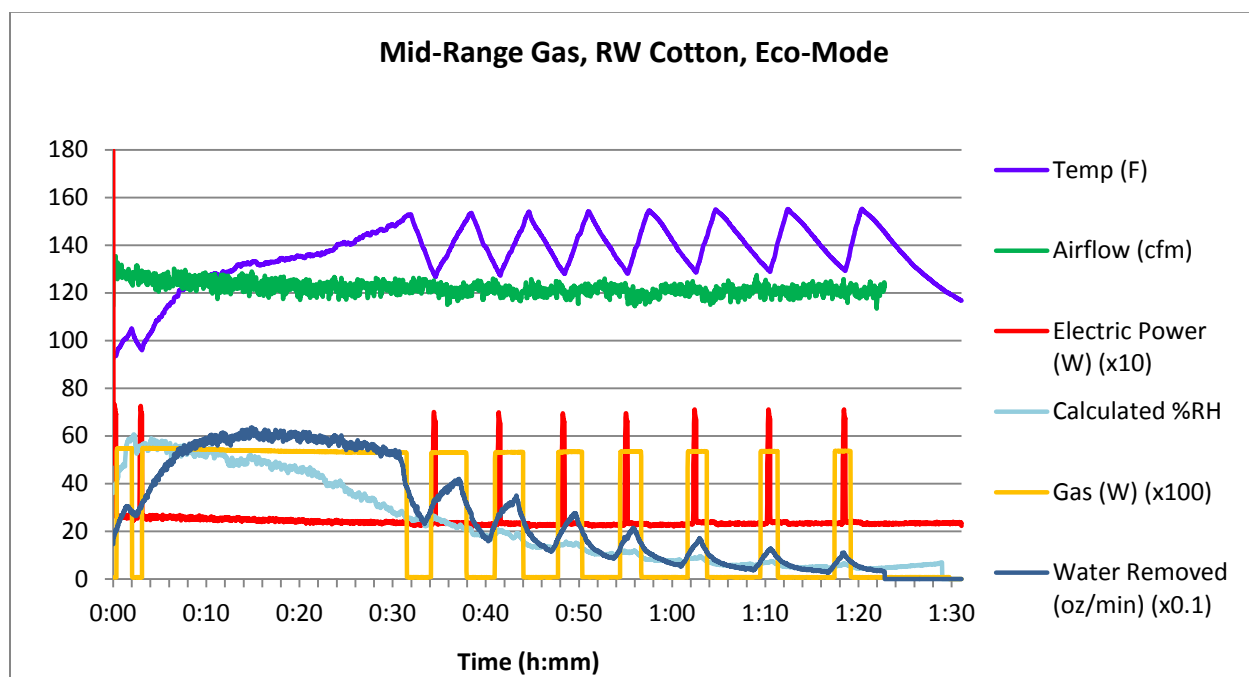


Figure 19. Mid-range gas dryer using RW cotton test and auto-termination with eco-mode, with 155 °F peak temperature, 4.45 kWh total energy use, and 0.0% RMC. Note the airflow meter stopped recording at ~1:20

Figure 20 and Figure 21 show the RW 50/50 cycle and its corresponding eco mode cycle of a mid-range gas dryer. Again, the peak temperatures are the same, and the eco mode allows the temperature to drop further. This leads to a lower average temperature and longer drying time from 27 to 30 minutes. The final RMC was 12% without eco mode versus 7% with eco mode using the same dryness setting. This led to a 22% *increase* in overall energy use and a decrease in overall efficiency from 52% to 48% for the eco mode.

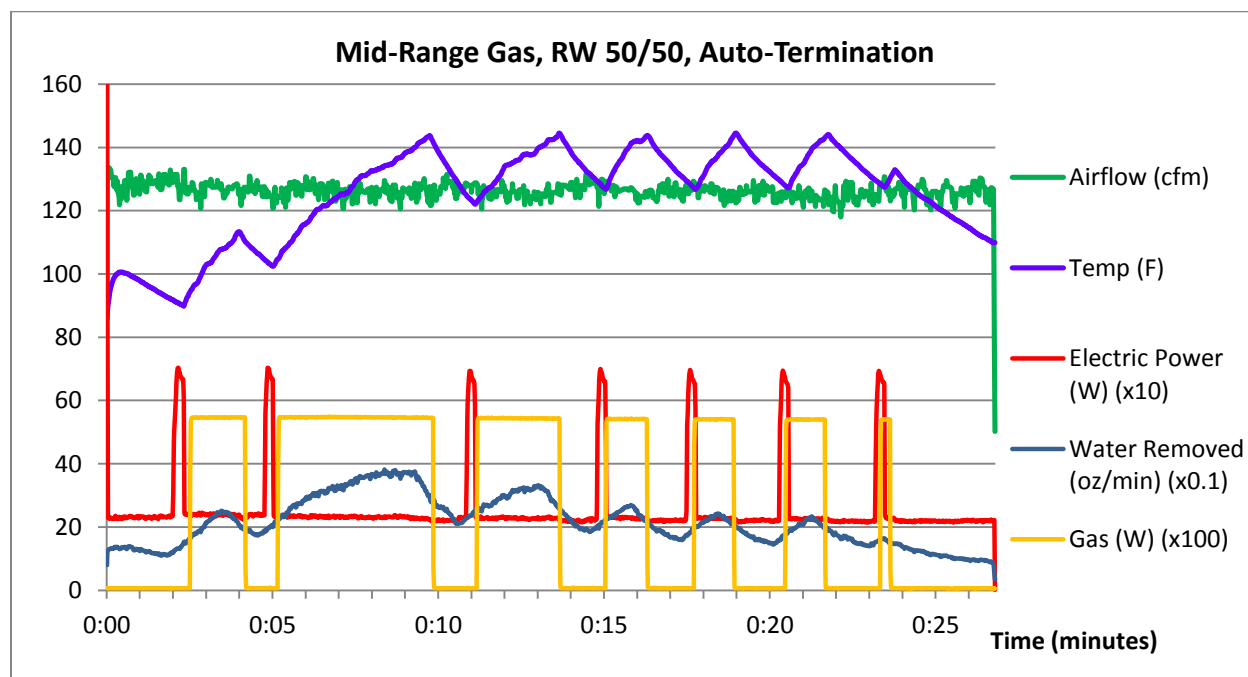


Figure 20. Mid-range gas dryer using RW 50/50 test and auto-termination, with 145 °F peak temperature, 2.07 kWh total energy use, and 11.51% RMC.

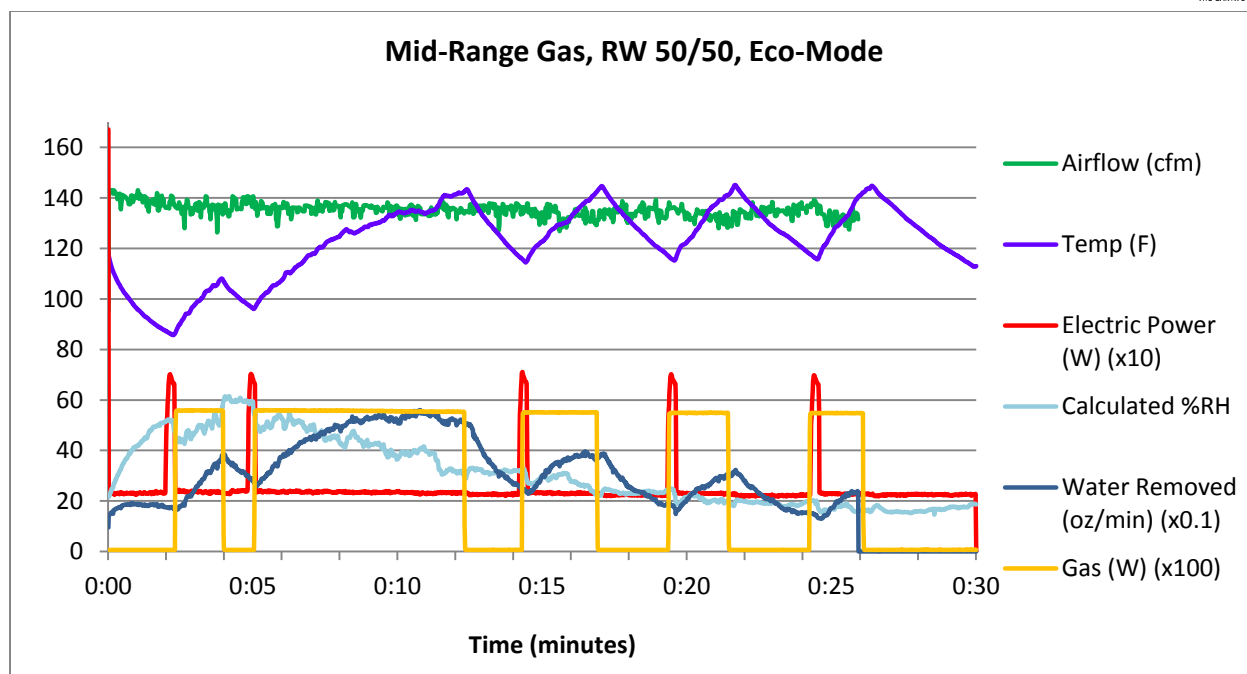


Figure 21. Mid-range gas dryer using RW 50/50 test and auto-termination with eco-mode, with 145 °F peak temperature, 2.20 kWh total energy use, and 6.75% RMC

Figure 22 and Figure 23 show the RW 50/50 cycle and its corresponding eco mode cycle of a mid-range electric dryer. The peak and minimum temperatures are the same, but the drying time decreased from 40 minutes to 27 minutes for the eco mode cycle. This achieved an overall 4% increase in efficiency, or more than 13% decrease in energy use. Unfortunately, the worsened performance in drying clothing negated the apparent benefits to using the eco mode cycle; the final RMC increased from 1% to 5% for the eco mode cycle.

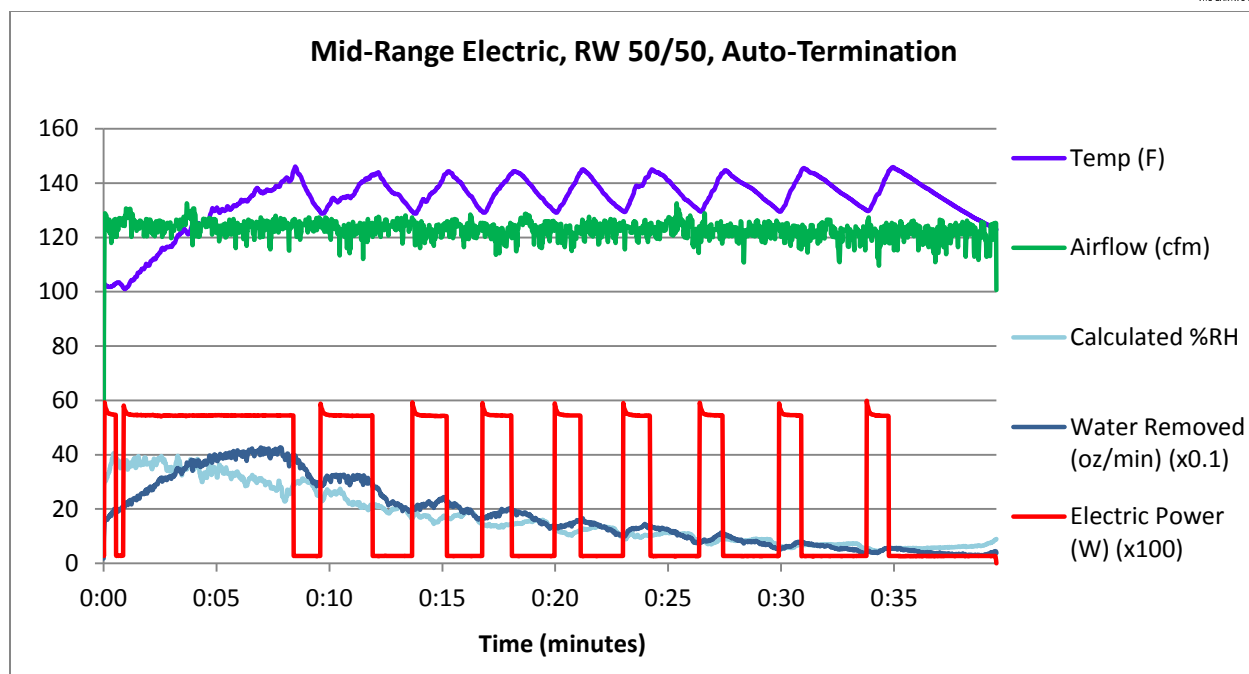


Figure 22. Mid-range electric dryer using RW 50/50 test and automatic-termination, with 146 °F peak temperature, 2.17 kWh total energy use, and 1.0% RMC

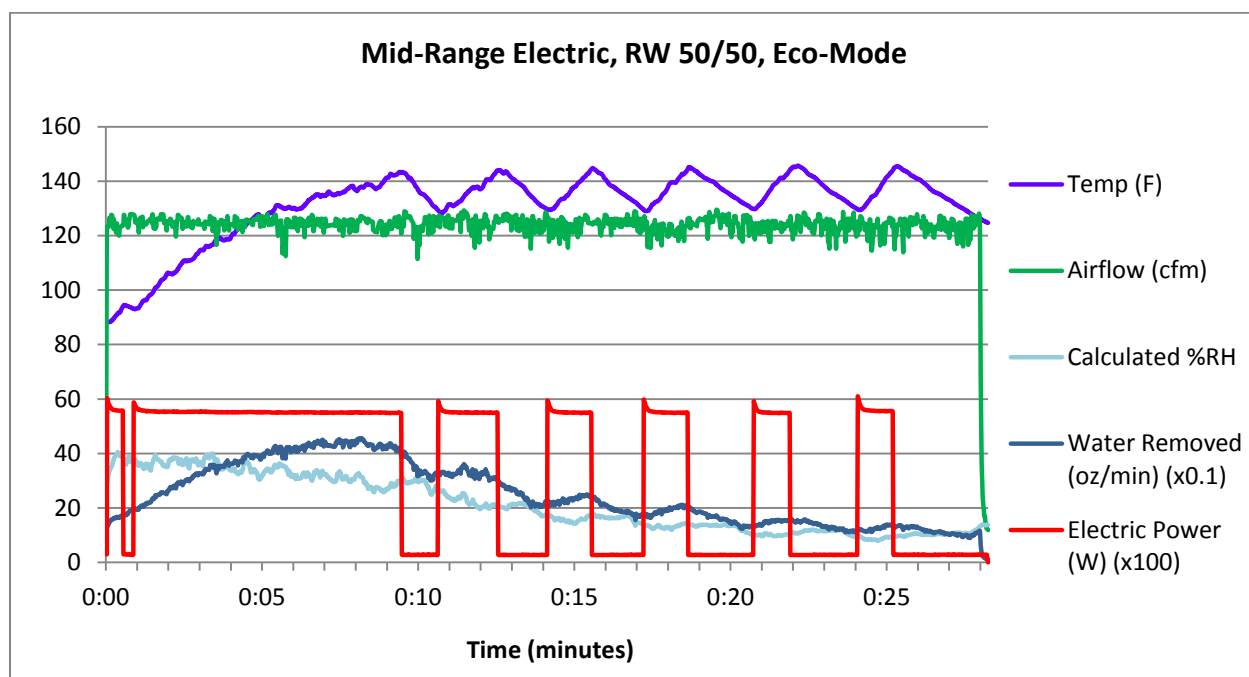


Figure 23. Mid-range electric dryer using RW 50/50 test and auto-termination with eco-mode, with 146 °F peak temperature, 2.02 kWh total energy use, and 4.76% RMC

Based on the initial testing we conducted, it does not appear that these eco modes, as currently implemented, are yielding any consistent efficiency gains. They may be saving energy in some cases by leaving the clothing less dry, but users could achieve the same effect by simply changing dryness settings or drying times. The eco modes have missed what appears to be a more promising opportunity for energy savings – to slow down the drying process for loads (by reducing heater and fan powers) in which drying times are not critical (single loads or the last load of the day) -- while still achieving the desired degree of dryness.

Condensing Dryers

We tested three compact, condensing dryers: one 240 V, one washer dryer combination (120 V), and one European heat pump. All three of these dryers have a closed internal air loop that is heated, picks up moisture in the drum, and is then cooled so the water can be condensed and discharged down the drain (or collected in a bin), instead of being vented outside of the home. This air loop is not easily accessible, so we did not measure the air flow rate, relative humidity, drum exit temperature, and water removed. A separate external air loop dumps the heat produced by the electricity consumption into the room air. Though it would have been easier to measure this air flow rate and temperature, we did not measure this airstream because the lack of moisture added does not provide as much useful information about the dryer's overall efficiency and performance.

Figure 24 and Figure 25 show the compact condensing dryer for the RW cotton and RW 50/50. It requires 240 V, so there were two phases from which to draw and measure power. The total power draw is made up of the two heaters, room air fan, internal air fan, and drum rotation (the latter two could be on the same motor). The 160 watts consumed during the final portion of the drying cycle appears to be the result of drum rotation and recirculation fans, but no heater power. The cause of the additional 200 watts of power consumption per phase between minutes 2 and 8 is unknown. Likewise, it is possible that some degree of modulation occurs between the 1:00 and 1:10 timeframe. Sub-metering of the power draw inside the unit would be required to conclusively describe how the power is being consumed by individual components of the dryer.

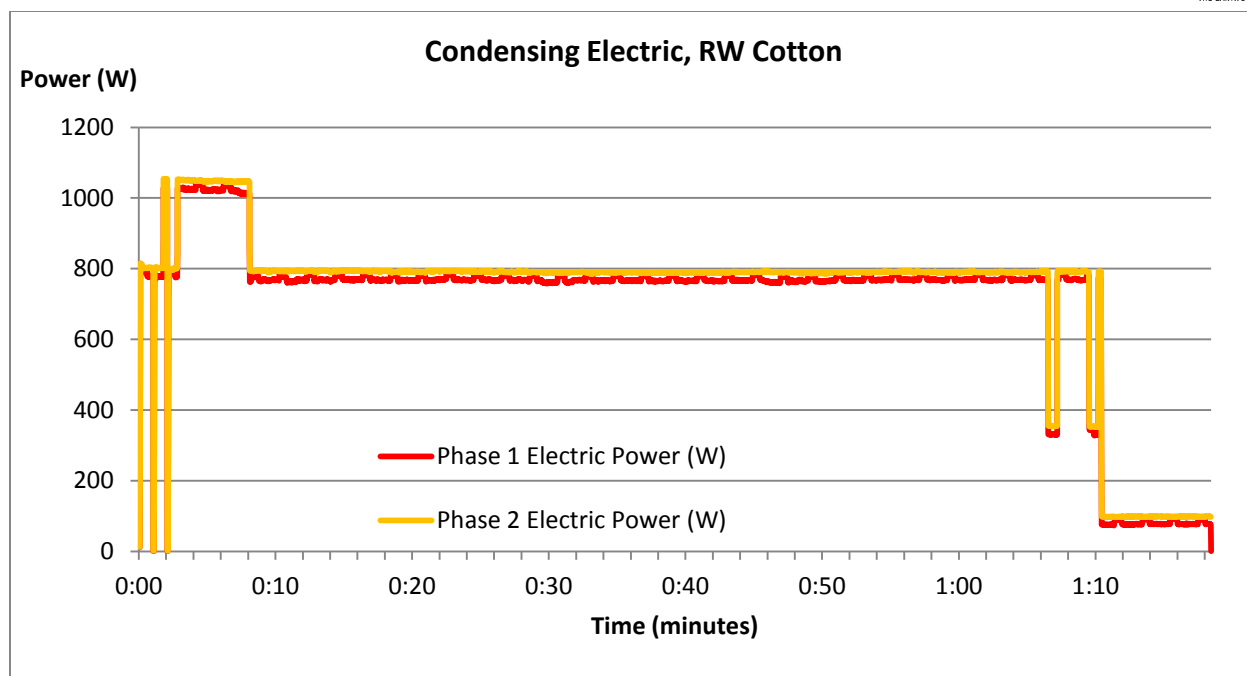


Figure 24. Condensing electric dryer using RW cotton test

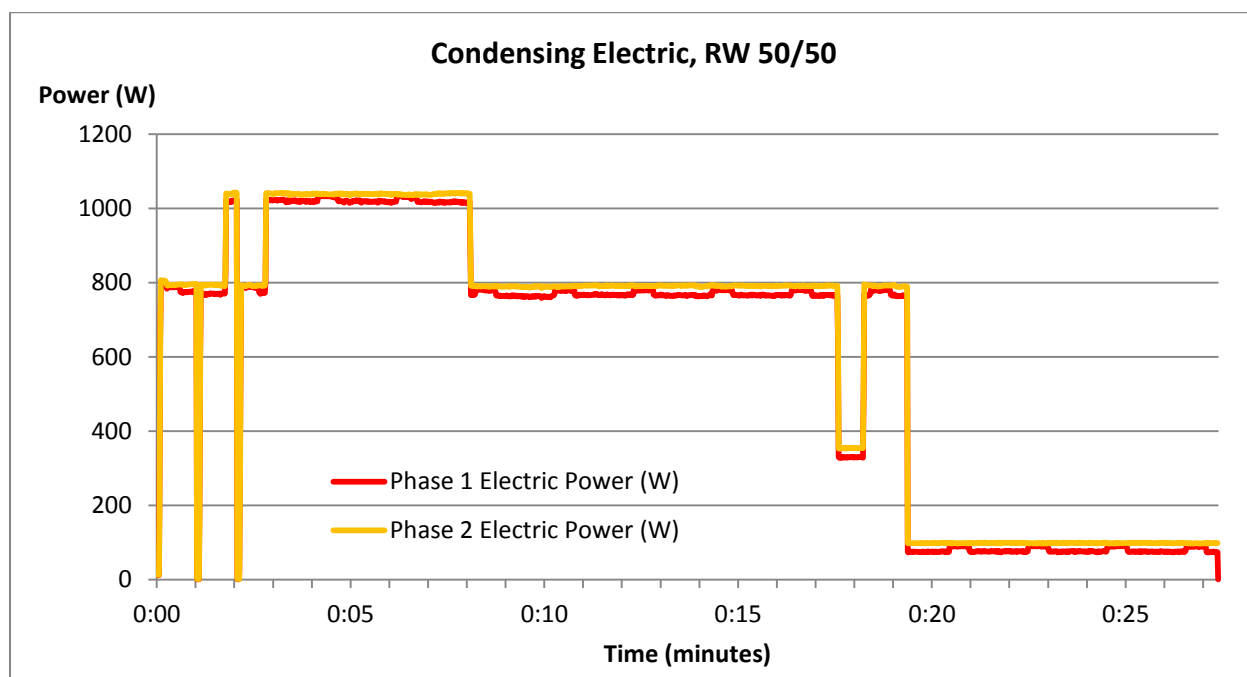


Figure 25. Condensing electric dryer using RW 50/50 test

Figure 26 shows the combination washer/dryer with RW cotton load. This dryer is 120 V, so there is only one phase of power draw. This displays simpler behavior than the condensing unit; the heater is on for the bulk of the cycle while the end of the cycle energy use is only to power the internal fan, drum, and possibly the external fan.

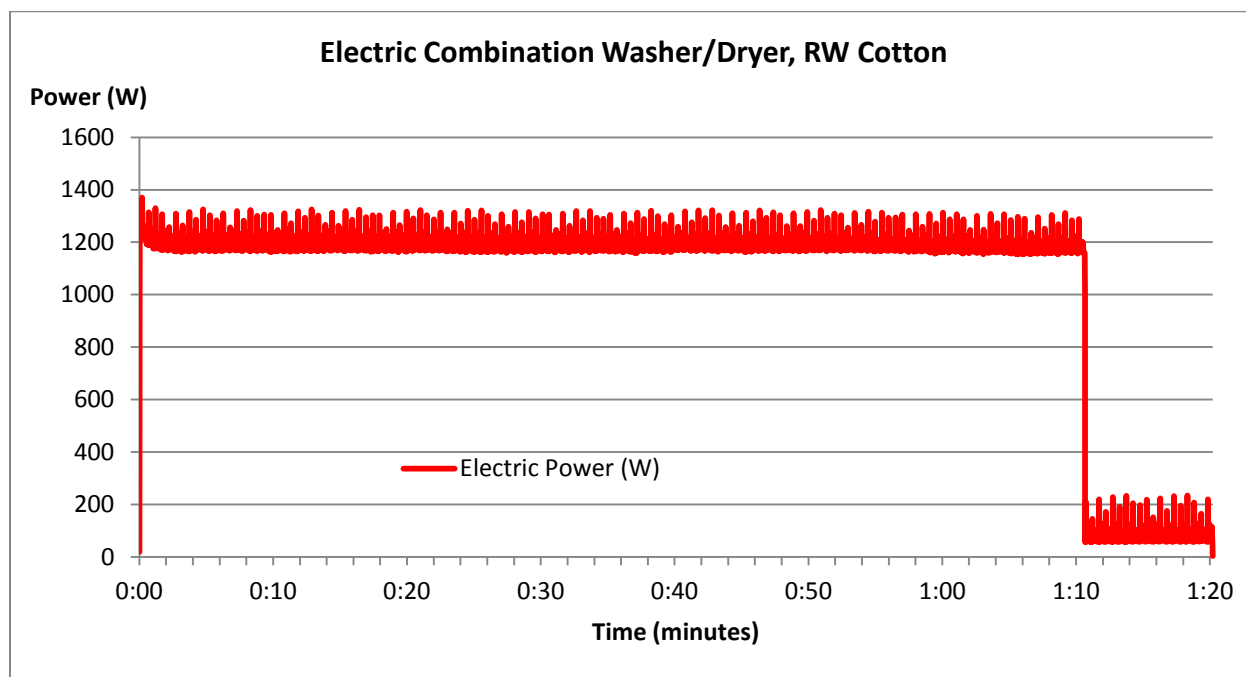


Figure 26. Electric combination washer/dryer using RW cotton test

We supplied the heat pump dryer with 230 V at 50 Hz. The power of the two fans and the drum is about 200 W for the heat pump (see Figure 27), which is higher than we observed in other compact condensing units. The other condensers also have a fan to circulate room air and the internal fan has to go through a heat exchanger. However, the heat pump adds an additional heat exchanger for the warming of the internal air (the conventional condenser dryers have a coil heater, which would have less flow resistance than a heat exchanger). Unlike in a conventional dryer, where about 7% of the total energy use is for the drum and the fan, it is more than 30% for the heat pump. The times when the power drops close to zero are when the drum and fan stop. The unit makes a noise during those intervals, likely associated with automatic weighing of the clothing.

The compressor power ramps up from about 300 W to 600 W over approximately 10 minutes. We believe this is because initially there is no temperature difference in the refrigerant on the two sides of the heat pump. Thus, if the temperature difference increases, the pressure difference would increase, affecting the power of the compressor motor. Therefore, it would be even more important for the heat pump to warm it up before running a test (or to distinguish between the energy use of single loads and the energy use of sequential loads).

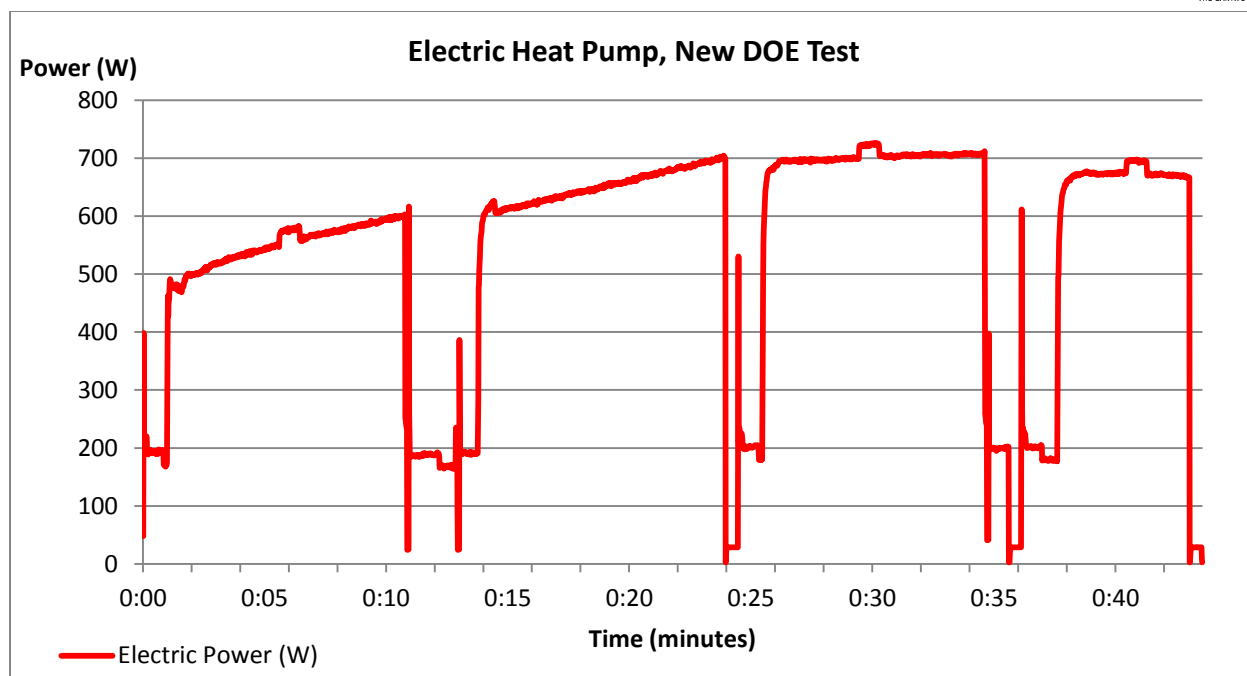


Figure 27. Electric heat pump dryer using new DOE test

For the 2011 DOE test load (3 pounds and 57.5% initial RMC), the heat pump was approximately twice as efficient as conventional dryers (130% efficiency versus 65%). However, for the RW clothing, it was only about 1.6 times as efficient (83% efficiency versus 53%) (see Figure 28). The major difference is the time spent when the clothing is nearly dry. In a conventional dryer, the heater cycles on and off. However, the heat pump stays on continuously at the end, so this could explain the difference. There may be differences in consumer preference for dryness between European and US users as well. Also, the manufacturer may be trying to avoid frequent compressor cycling by designing the compressor to run in a more constant fashion.

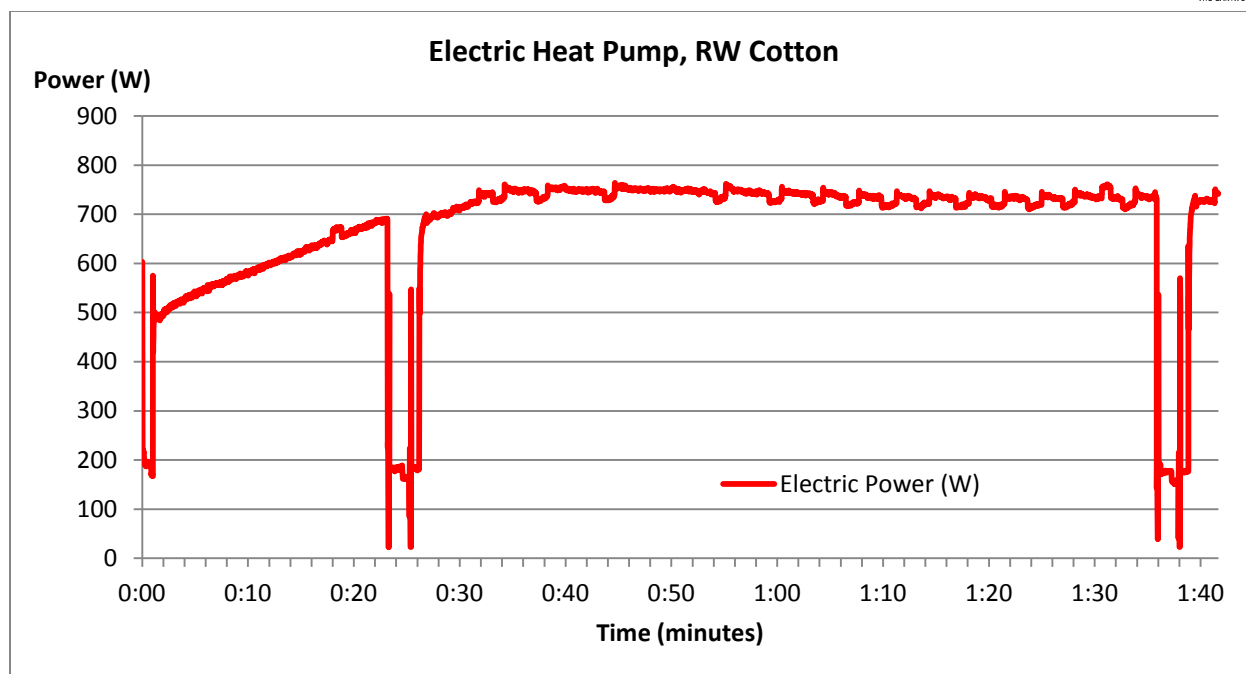


Figure 28. Electric heat pump dryer using RW cotton test

VIII. Discussion of Various Dryer Efficiency Metrics

Clothes dryer efficiency can be measured a number of different ways. The 2011 DOE test procedure uses energy factor (EF) as its sole efficiency metric. The EF is defined as pounds of dry clothing dried per kWh of site energy. Other metrics proposed in our 2009 NRDC report include site efficiency (energy to evaporate the water removed divided by the site energy), source BTUs per pound of water removed, energy cost per water removed, and source CO₂ emissions per pound of water removed.⁶ Another possible metric is CO₂ equivalent emissions per pound of water removed, including upstream (mining, drilling, refining, transportation, power plant operation, etc.) energy, methane leaks, and refrigerant leaks. This latter metric is subject to the additional uncertainties in the leaks and variability due to the chosen time horizon as the lifetime of methane and refrigerants is significantly less than CO₂. Nonetheless, because conventional electric dryers are less penalized by greenhouse gases other than CO₂, this yields the surprising result that the efficient electric dryer has lower GHGs than the heat pump.

The rankings of dryers for the source BTUs per pound of water removed, energy cost per water removed, and source CO₂ per pound of water removed are the same, meaning they are more robust (see Table 5). To the extent that ENERGY STAR and other federal programs are creating energy efficiency specifications for the purpose of reducing greenhouse gas emissions and

⁶ Paul Bendt, Chris Calwell, and Laura Moorefield, "Residential Clothes Dryers: An Investigation of Energy Efficiency Test Procedures and Savings Opportunities," Ecos Consulting report for Natural Resources Defense Council, November 6, 2009.

associated climate risk across multiple fuel types, it may make sense to link fuel-neutral efficiency metrics to the CO₂ reduction goal itself.

Table 5. Dryer comparisons using different efficiency metrics⁷

Dryer technology	2011 DOE Test			Ecova Tests					Efficient Gas (Estimate)
	Std Electric	Std Gas	Heat Pump	Std Electric	Efficient Electric	Std Gas	Heat Pump	Condenser	
Energy factor	3.89	3.68	7.60	2.84	3.62	2.50	3.83	2.96	3.33
Site Efficiency	65.9%	61.5%	133%	54.3%	63.0%	47.4%	77.8%	45.0%	63.2%
Site kWh-equivalent / lb of water removed	0.47	0.50	0.24	0.59	0.49	0.65	0.40	0.68	0.49
Pounds CO ₂ emitted / lb of water removed	0.62	0.22	0.32	0.77	0.65	0.31	0.52	0.90	0.23
Pounds CO ₂ equivalent emitted / lb of water removed	0.83	0.36	0.51	0.88	0.73	0.48	0.83	1.22	0.36
Source BTUs / lb of water removed	5540	1940	2900	6950	5800	2680	4700	6900	2200
Source kWh / lb of water removed	1.6	0.6	0.8	2.0	1.7	0.8	1.4	2.0	0.6
Energy cost (cents) / lb of water removed	4.7	2.2	2.4	5.9	4.9	3.0	4.0	6.8	2.24

⁷ The following assumptions were used in generating the values in the above table:

- kWh to evaporate 1 lb water: 0.308
- US average power plant kg CO₂/kWh: 0.6 (Life cycle analysis CO₂ is 0.65: Improving Life Cycle Assessment of US Grid Electricity. 6 February 2010. So direct is 0.6.)
- GHGs from refrigerants as a fraction of emissions from energy generation: 25%
- Average power plant efficiency (Higher heating value): 32%
- Electric transmission, distribution, and building wiring efficiency: 90%
- Efficiency of mining and transporting fossil fuels: 92% (Climatic Change (2011) 106:679–690 DOI 10.1007/s10584-011-0061-5 "Methane and the greenhouse-gas footprint of natural gas from shale formations," Robert W. Howarth, Renee Santoro, Anthony Ingraffea)
- Mass global warming potential of methane/CO₂ (average of 20 and 100 yr): 70 (Climatic Change (2011) 106:679–690 DOI 10.1007/s10584-011-0061-5 "Methane and the greenhouse-gas footprint of natural gas from shale formations," Robert W. Howarth, Renee Santoro, Anthony Ingraffea)
- Natural gas leakage: 5% (Climatic Change (2011) 106:679–690 DOI 10.1007/s10584-011-0061-5 "Methane and the greenhouse-gas footprint of natural gas from shale formations," Robert W. Howarth, Renee Santoro, Anthony Ingraffea)
- Electricity retail cost: 10 cents/kWh (EIA 2011 (data for 2009))
- Natural gas cost: 120 cents per therm (<http://www.eia.gov/dnav/ng/hist/n3010us3m.htm>)

IX. Discussion of Additional Opportunities for Improving Dryer Efficiency

The technologies and approaches described below are additional opportunities for making dryers more efficient. We did not test these technologies directly. All of the approaches described below can be applied to both gas and electric dryers.

Heater and Fan Modulation

As the final RMC of the clothing falls below about 10%, the surface of the clothing is no longer saturated. This means that the internal air does not pick up as much humidity, and it leaves the drum at a higher temperature. The higher exit temperatures lead to decreased cycle efficiency and greater risk of damage to clothing. The conventional solution to this problem is cycling the heater on and off. However, the more efficient solution to this problem is lowering the heater power *and* air flow rate simultaneously. This gives more time for the air to pick up moisture. Furthermore, if the fan motor is slowed efficiently, halving the airflow reduces the fan power by a factor of eight. Yet conventional dryers use a single motor to power the fan and spin the drum. In order for effective drying of the clothing, the clothes must be thrown into the air, which would not occur at half the drum spin rate. Therefore, separate motors are required for the drum and fan.

The DOE estimates that modulating dryers would save approximately 6% of the overall energy use.⁸ We believe this is a reasonable estimate for DOE test cloths dried to ~4% final RMC. However, testing RW clothing necessitates that the dryer terminate at a much lower final RMC to fully dry clothing with different thicknesses and overlap regions. Because as clothes become more dry they require increasingly more energy to remove water, the dryer spends much more time with the clothing nearly dry than mostly wet. If a modulating dryer is used during this last drying phase to dry RW clothing, a more realistic energy savings estimate would be 20% of overall energy (TIAX found 25% savings with a large RW load, and about 12% savings with a small RW load).⁹

Recirculation

Recirculating the air has a similar effect to slowing the air down, but it does not have the advantage of lower fan energy that slowing the air down does. The DOE estimates that the incremental costs of recirculating air would be greater than modulation. More research is likely warranted here, since recirculation could also help during the warm-up period at the beginning of a drying cycle. During this timeframe, the objective is to warm up the drum, the clothes, and the air in the drum to the point where evaporation can begin to occur more rapidly. During this period, there is little to be

⁸ Office of Energy Efficiency and Renewable Energy, Department of Energy, "Energy Conservation Program: Energy Conservation Standards for Residential Clothes Dryers and Room Air Conditioners: Direct final rule" Vol. 76, No. 77, Thursday, April 21, 2011.

⁹ Peter Pescatore and Phil Carbone, "High Efficiency, High Performance Clothes Dryer," Final TIAX Report to: Department of Energy, March 31, 2005.

gained from venting the cool, dry air, and it might make more sense to recirculate that air until a particular moisture level has been achieved, and then begin to vent it.

Efficient after-cycle behavior

In order to prevent wrinkling of clothing, the clothes are sometimes tumbled after the cycle is done. With a typical power of 200 W and a typical time of one hour,¹⁰ this consumes 0.2 kWh, or about 7% of the cycle energy. One simple solution for reducing this energy use is tumbling the clothes periodically, which some of the dryers we tested did, approximately 10% of the time. Another approximately factor three reduction in energy use could be achieved by only spinning the drum and not running the fan, which is possible with modulating dryers.

Future Eco Mode

There is a strong desire among American consumers to have the drying time equal to the washing time, to allow for serial loads.¹¹ However, this washing time depends on the type of washer, as front loading washers typically take longer. The drying time also depends on the load weight and synthetic content, which lead to different initial RMC levels out of the washer.

The idea of eco-mode was to save energy but increase drying time. Our testing shows that the dryers did not really achieve this goal. This is not surprising, because simply lowering the duty cycle of the heater (or even reducing the heater power) while keeping the fan speed constant does not save significant energy.¹² However, an effective eco-mode would be possible in the future by using a modulating dryer; the entire drying cycle would be done at lower heater power and fan speed. This is already being done in the compact 120 V dryer, and the energy savings is ~20%. It is true that the drying time is ~60% longer, so this would likely not work with serial loads.

Serial loads have the advantage of dryer being hot at the beginning of the loads after the first load, which leads to a few percent energy savings. This small percentage energy savings is greatly counteracted by the ~20% energy savings of drying slowly in individual loads.

The energy savings in fast or slow drying modes of going from one half heater power and fan flow rate to one fourth heater power and fan flow rate would be smaller than the energy savings of going from full heater power and fan flow rate to one half heater power and fan flow rate. However, the incremental cost could be smaller as well, so it might make economic sense.

¹⁰ Office of Energy Efficiency and Renewable Energy, Department of Energy, “Energy Conservation Program: Energy Conservation Standards for Residential Clothes Dryers and Room Air Conditioners: Direct final rule” Vol. 76, No. 77, Thursday, April 21, 2011.

¹¹ Peter Pescatore and Phil Carbone, “High Efficiency, High Performance Clothes Dryer,” Final TIA Report to: Department of Energy, March 31, 2005.

¹² Office of Energy Efficiency and Renewable Energy, Department of Energy, “Energy Conservation Program: Energy Conservation Standards for Residential Clothes Dryers and Room Air Conditioners: Direct final rule” Vol. 76, No. 77, Thursday, April 21, 2011.

A concern with slower drying is that there would be more wear and tear on the motor, belts, and bearings. However, we have estimated that the increase in cost to make these components last the life of the dryer with more hours of operation is significantly smaller than the energy savings. There is also concern that the increased tumbling would cause more clothing damage, but we believe this is counteracted by the fact that the clothing would be at lower temperature.

The extreme case of drying time is using no heat. This would take approximately 4 hours to dry a load¹³, albeit it is very dependent on the ambient temperature and relative humidity. In addition to concerns of wear and tear on the motor, belts, and bearings and the increased tumbling of the clothing, there is also much more air exhausted per load, so the HVAC impacts would be significantly larger (though there would be a ventilation benefit – see Discussion of HVAC Impact).

Exhaust Heat Exchanger

The DOE Direct Final Rule notes that an exhaust heat exchanger (also known as an inlet air preheater – see Figure 29) can save 14% of the total dryer energy use if it condenses moisture.¹⁴ The DOE rule claims that stainless steel or glass must be used in the heat exchanger for this scenario to prevent corrosion. However, air conditioners use aluminum fins on the air side and have significant hours per year of condensation, so they can obviously handle potential issues with corrosion. Furthermore, the heat exchanger for a condensing dryer we tested appears to use aluminum. Both of these applications do not have the advantage of a vented dryer that would dry out the heat exchanger at the end of each cycle. Therefore, we believe that an exhaust heat exchanger can be made from lower-cost materials.

¹³ Paul Bendt, Chris Calwell, and Laura Moorefield, “Residential Clothes Dryers: An Investigation of Energy Efficiency Test Procedures and Savings Opportunities,” Ecos Consulting report for Natural Resources Defense Council, November 6, 2009.

¹⁴ Office of Energy Efficiency and Renewable Energy, Department of Energy, “Energy Conservation Program: Energy Conservation Standards for Residential Clothes Dryers and Room Air Conditioners: Direct final rule” Vol. 76, No. 77, Thursday, April 21, 2011.

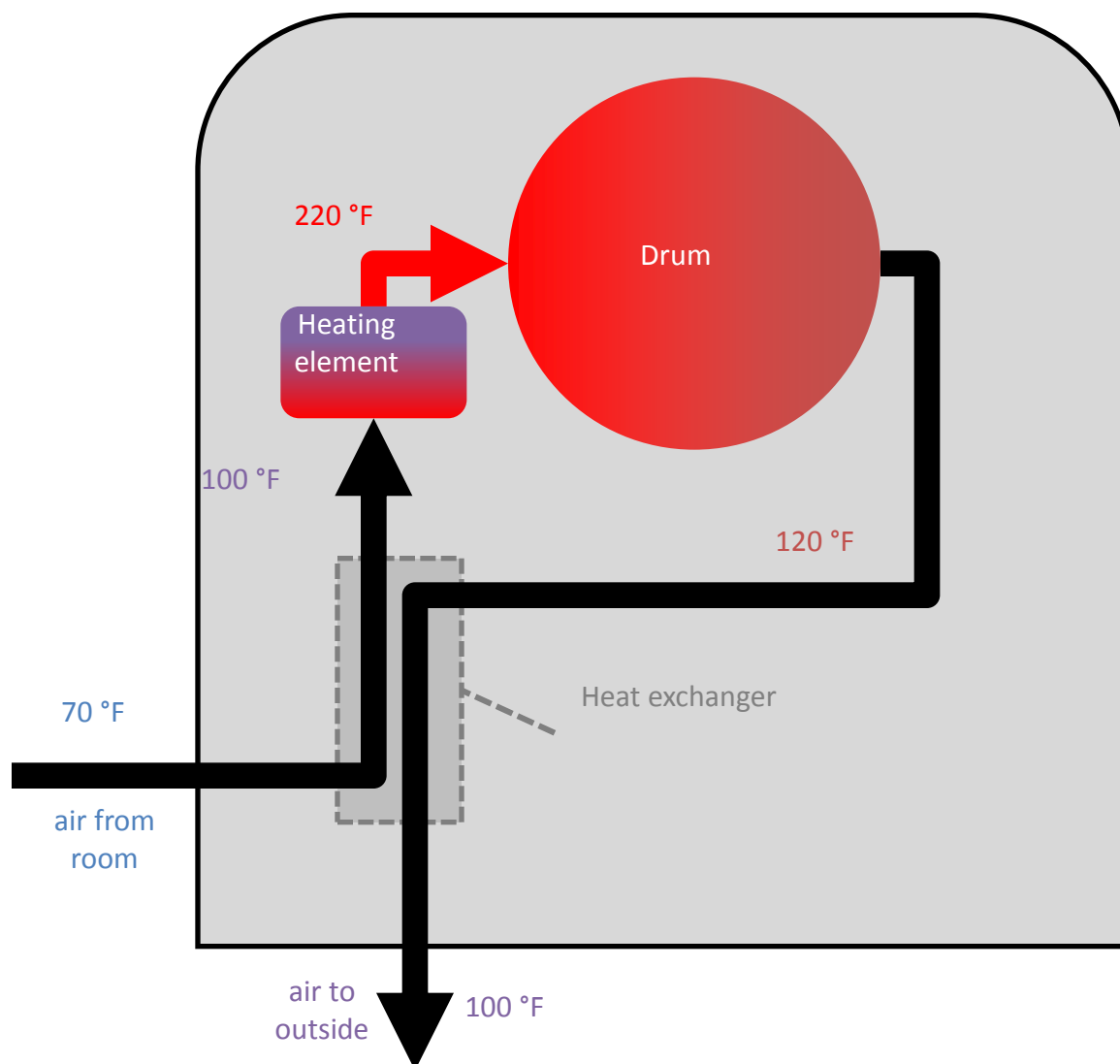


Figure 29. Vented dryer with exhaust air-to-air heat-exchanger

One solution for the clogging of the heat exchanger is storing condensed water and using that to periodically flush out the heat exchanger (the method used by the heat pump dryer we tested). Another solution is a removable heat exchanger that can be rinsed manually (the method used by the condensing dryer we tested). Finally, there is a new technology that combines a heat exchanger and a fan: it is made of metal and has a very small air gap over which heat can be transferred (see Figure 30).¹⁵ This figure only shows one side of the heat exchanger; in a dryer application, there would be two of these impellers, one inverted underneath the other. As can be seen in the case of computer chip cooling, the heat sink will clog, but the fan will generally not. Therefore, this spinning heat exchanger should not clog.

¹⁵ Jeffrey P. Koplow, "A Fundamentally New Approach to Air-cooled Heat Exchangers," Sandia Report, SAND2010-0258, Unlimited Release, Printed January 2010.

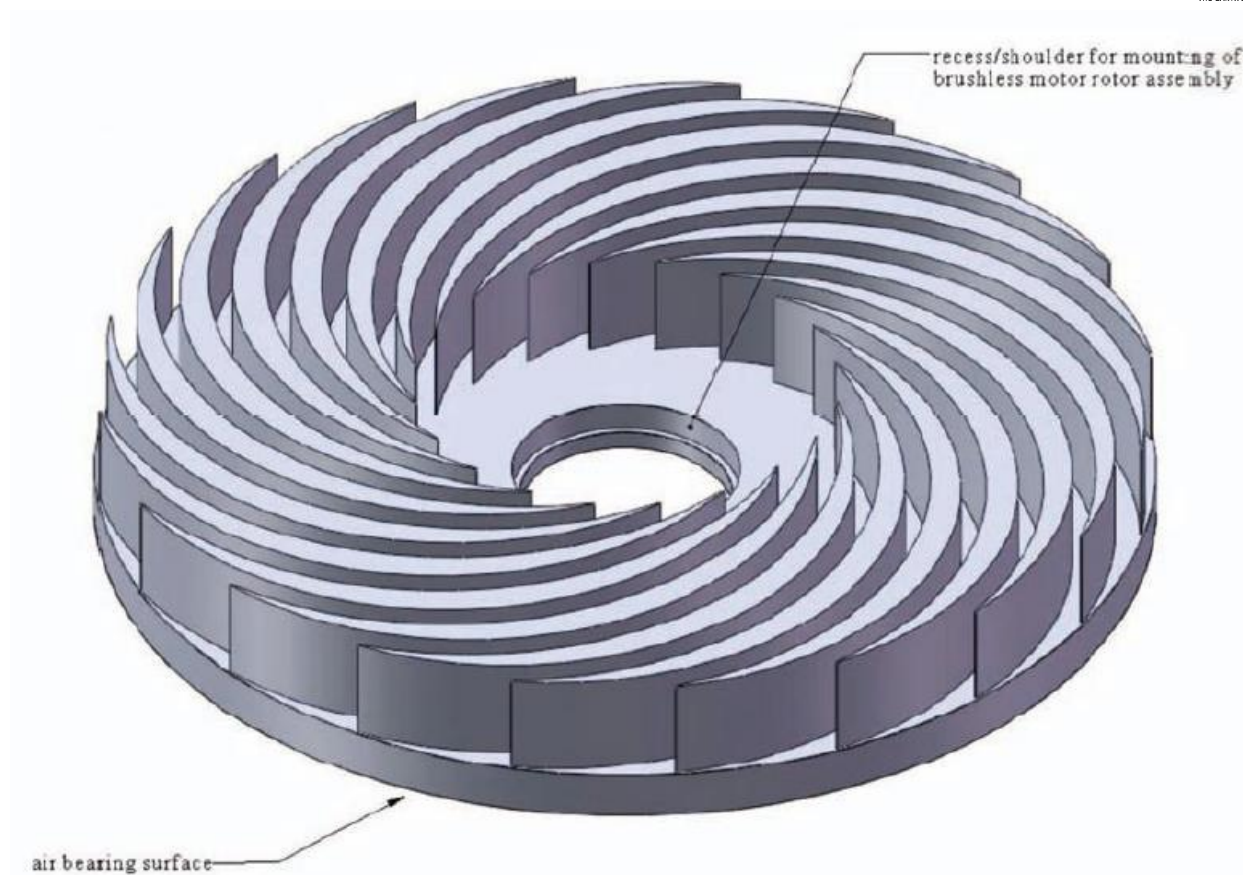


Figure 30. Combination heat-exchanger and fan

The heat exchanger would save energy during the bulk drying stage, when modulation would not be used for fast drying. Energy would also be saved near the end of the cycle whether there was modulation or not. For slow drying, the exhaust air temperature would be lower, so a heat exchanger could save less energy in this case.

X. Discussion of HVAC Impacts

Conventional vented electric dryers draw air from the room and exhaust it outside the house. The total air entering the house must equal the total air exiting the house. Therefore, the dryer exhaust lowers the pressure inside the house, which increases infiltration but also decreases exfiltration (air flow out the cracks), so the increase in infiltration is only about 60% as large as the dryer flow rate (see Figure 31).

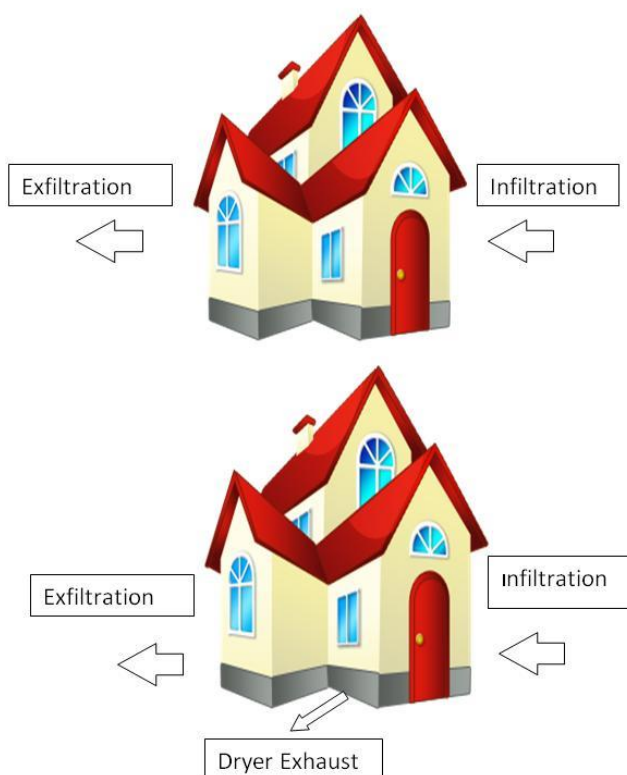


Figure 31. House infiltration and exfiltration without dryer (upper figure) and with dryer (lower figure)

The house depressurization means that it is more likely for flue gases from furnaces, water heaters, and fireplaces to be drawn into the indoor space when starting up. However, when these devices are not starting up, the dryer draws clean air, so it is roughly a wash for heater pollution. Some investigators have claimed that the depressurization caused by the dryer would increase radon problems. When the atmosphere has high pressure, it will prevent radon from going to the house, and when the atmosphere has low pressure, radon will come out of the ground into the house. These variations are roughly 1000 Pa. Depressurization from the dryer is unlikely to be more than 1 Pa. Therefore, the major factor determining whether radon will go into a house is the meteorological variations of high pressure and low pressure, not the dryer.

The dryer exhaust creates a net benefit for tobacco smoke, VOCs, asthma/allergy, and infectious diseases. A commercial study found that the indoor air quality benefits of doubling ventilation were 14 times the increased HVAC cost.¹⁶ There is not a uniform standard for active ventilation in new residential buildings, and few older low-rise residential buildings have active ventilation. Instead, many designers rely on infiltration to maintain air quality, often citing an average air changes per

¹⁶ William J. Fisk, "Estimates Of Potential Nationwide Productivity And Health Benefits From Better Indoor Environments: An Update," Published as Chapter 4 in *Indoor Air Quality Handbook*, eds: J. D. Spengler, J.M. Samet, and J.F McCarthy, McGraw Hill.

hour throughout the year. However, this results in significant variation in air quality, which is likely to be worse overall than for the commercial case of required constant active ventilation.

Furthermore, in the case of vented dryers, users are already paying to move the air (in fact, for condensing dryers, the fan energy use is even greater). Therefore, even though there are HVAC penalties associated with vented dryers, the economics of dryer ventilation increasing indoor air quality is likely to be even stronger than for the case of increasing active ventilation in commercial buildings, i.e. greater than 14 to 1.

The HVAC energy impacts of dryer ventilation depend on the climate, efficiency and fuel source of the heating and cooling equipment, and whether or not the dryer is located in an unconditioned space. When integrated over a year, these impacts are around 10%.

For ventless dryers (electric resistance or heat pump), all of the electricity going into the appliance is turned into heat that is then added to the room¹⁷. This is beneficial in the heating season, and detrimental in the cooling season. The impact is significantly greater than for vented dryers, and is generally positive in the United States. However, the net HVAC energy savings from ventless dryers would need to be weighed against the likely health benefits of greater venting in many homes. The fact that heat pump dryers can also be designed to be vented, and that there are some efficiency benefits associated with venting some of the moisture, further complicates this issue. Field research to quantify the net outcome would be worth pursuing.

XI. Opportunities for Future Research

One area of future research is demonstrating the repeatability of using RW clothing. The fact that our very different cotton and 50% synthetic loads gave similar efficiency results is encouraging, but there were counteracting factors of greater load size for the cotton but higher dryness settings. We have not yet done the study of repeating the same load on a given dryer, but this is important because of the possibility of the moisture sensing only sensing one article of clothing. Another repeatability test is recognizing that there will be more variability in the RW articles of clothing used than there is with the DOE test cloths. There is already significant variation in the DOE test cloths, which is why the lot must be specified, but we believe this is more for the initial RMC with a given spin cycle, rather than a different drying performance with a specific initial RMC. If the initial RMC of RW clothing is controlled, we believe the variability due to changes in synthetic quantity of different articles will be small. The main factors to control are the average and variation in thickness of clothing, because these affect the wetted surface area with a given dry weight of clothing, and also the final RMC at which the clothing can be considered uniformly dry.

A related question is: what are the energy and drying time implications of the practice that some people employ of removing specific dry articles of clothing before the cycle is finished.

¹⁷ Assuming there are no leaks.

Future testing could include monitoring the clothing temperature. Another area of future research is modifying existing dryers for modulation, exhaust heat exchanger, and/or recirculation to assess the impact on dryer efficiency.

A promising modification for heat pumps would be to use a smaller heat pump with a low temperature lift (greater efficiency, lower cost per heating capacity) and using electric resistance to increase the temperature of the air and allow faster drying time “hybrid heat pump.” Then if slower drying is tolerable, it could go into heat pump mode only.

XII. Acknowledgments

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XIII. Appendices

Test Equipment

We used a scale with a maximum capacity of 60 pounds that displays weight to one hundredth of a pound to weigh test loads before we put them in the washer, before the dryer, and after any test runs (see Figure 32).



Figure 32. Scale used to weigh dryer test loads accurate to 1/100th of a pound

For the gas dryers, we inserted an Alicat gas meter in line with the gas line before the gas valve on the dryer. We completed initial gas dryer testing to ensure that the gas meter did not impede upon the gas flow to the dryer. Almost identical saw-toothed temperature signatures with and without the gas meter in the line demonstrated that the gas meter was not meaningfully altering dryer performance. We recorded energy usage on a Yokogawa WT1600 (Figure 33) or Yokogawa WT500 (Figure 34). We data logged the power signature of gas dryers, other 120 V dryers, and the heat pump dryer on one channel (phase) while 240 V dryers used two channels (phases) to record the total power usage.

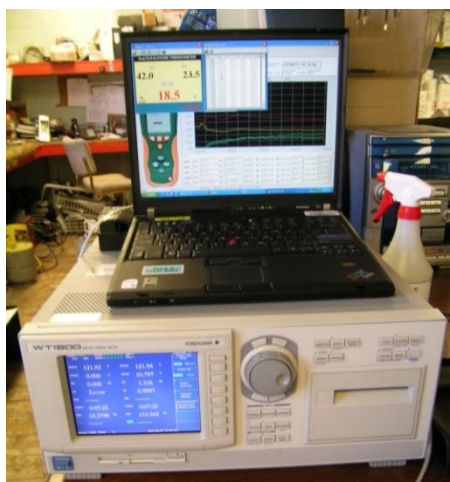


Figure 33. Yokogawa WT1600



Figure 34. Yokogawa WT500

We logged the exhaust temperature and percent relative humidity (% RH) using an HD500 sensor (see Figure 35). A more accurate measurement of exit temperature was recorded using the EV15, which uses wet bulb and dry bulb temperatures. The wet bulb sensor had a strip of cloth that was soaked in water so that it would remain moist throughout the dryers test runs. Finally, we measured exit air velocity in feet per minute, using an HD300. This piece of equipment had an axial vane anemometer at the end of an 18" plastic tube that had a diameter of 3 inches compared to the 4 inch diameter of the plastic tube (see Figure 35). We have estimated that the flow resistance of this entire apparatus is approximately equivalent to 2 feet of flex ducting. Therefore, the test procedure could be modified to include this apparatus and only 6 feet of flex ducting instead of the current DOE requirement of 8 feet.



Figure 35. Back of dryer being tested showing EV15 (left), HD300 (second from left) with a fan at the back of the 18 inch plastic tubing and HD500 (top right).

We used an additional eight foot duct to vent the exhaust air and simulate RW dryer conditions (per the DOE test procedure). The duct served to decrease overall airflow out of a dryer and we attached it to the end of the 18 inch plastic tube, which we attached to the dryer itself (see Figure 36). There were no more than two sharp curves when placing the duct so as to not add more impedance to the exit airflow.



Figure 36. We directly connected the 18" plastic tube to the back of the dryer and all of the HD500, HD300 and EV15 measure the exit parameters in this tube. We then attached the eight foot duct to the end of this plastic tube.

For five of the dryers that we tested at Ecova facilities, a centrifuge was used to remove excess water and make test loads conform to the appropriate initial RMC (see Figure 37 for a side and top view of The Laundry Alternative, Inc.).



Figure 37. Side view (left) and top view (right) of the centrifuge used to make test loads conform to the appropriate initial RMC.

Other Real World Test Cloths

As mentioned in our Test Loads section, the IEC and Australian/New Zealand clothes dryer test procedures use RW clothing to evaluate dryer performance. The IEC has two test loads, one cotton and one easy care, which is similar to our approach (see Table 6).

Table 6. Overview of test loads used in the IEC and Australian New Zealand clothes dryers test procedures.

Test Procedure	IEC 61121		AS/NZS 2442
Number Test Load Types	Cotton	Easy care	Single
Test Load(s) Composition	Conditioned sheets, pillowcases, and hand towels	Equal number men's shirts and pillowcases	Sheets, Bath towels, Tablecloths, Shirts, T-shirts, Pillow cases, Undershorts, Wash cloths, Handkerchiefs
Test Material	All cotton	Some synthetic content	Mostly cotton (All items 100% cotton except for the Shirts, which have 50% - 65% polyester content)
Load Size	Variable based on dryer's rated maximum capacity		Variable based on dryer's rated maximum capacity

Table 7 below shows the variation in cloth thicknesses and material content for AHAM 1992, AHAM 2010, and AZ NZS 2442 test loads, all of which use RW clothing instead of a standard single ply test cloth.

Table 7. Comparison of AHAM 1992, AHAM 2010, and Australian/New Zealand RW clothing test loads.

Test Procedure	Cloth Items	Material		Range of Thickness of Ply (g/m ²)	
		Percent Cotton	Percent Synthetic	Thin	Thick
AHAM 1992 Energy Test	Sheets, tablecloths, shirts, bath towels, T-shirts, pillow cases, shorts, wash cloths, handkerchiefs	100%	0%	88	411
AHAM 2010	Bed sheets, pillow cases, towels	100%	0%	185	220
AS NZS 2442	Sheets, tablecloths, shirts, bath towels, T-shirts, pillow cases, undershorts, wash cloths, handkerchiefs	93%	7%	76	667

RW Clothing Test Loads

Two test loads of very different load sizes and composition were chosen to capture the range of possible scenarios of clothing being dried in the real world. We tried to choose test loads that are representative of clothing that would be found in a given household and include items of different thicknesses to better assess a dryer's ability to determine when a load of clothing is dried (see Table 8 and Table 9).

Table 8. RW clothing test loads for full sized dryers

	Test Load	Weight (lbs)	Items Included
(1)	RW 50-50	5	Black pants 2XL, black pants XL; 2 boxers, checkered dress shirt, sheet set (flat sheets, 1 pillowcase), 10 pairs thick socks, 2 pair thin socks
(2)	RW Cotton	10	Dark jeans, jeans 42x32, jeans 32x34, bath towel, 3 briefs; grey t-shirt, 6 white t-shirts, 5 white briefs, hand towel, towel, small bra

Table 9. RW clothing test loads for compact dryers.

	Test Load	Weight (lbs)	Items Included
(1)	RW 50-50	2	swim trunks, large bra, 2 boxers, checkered dress shirt, 3 pair thick socks, 2 pillowcases, 1 thin sock
(2)	RW Cotton	4	jeans 42x32, brief; 3 white briefs, grey t-shirt, 4 white t-shirt

As shown by each pair of items in Table 10, the same type of clothing can have different thicknesses, as well as different cotton content (i.e. items 5 and 6).

Table 10. Full Sized Dryer Real World Cotton Test Load items, the approximate thickness of cloth, cotton content, and total weight of that item (may include multiple copies of an item e.g. 6 white t-shirts)

Item	Thickness (lbs/m ²)	Content (% cotton)	Weight (lbs)
dark jeans (1)	1.298	100	1.14
jeans 34x30 (2)	1.538	100	1.79
jeans 42x32 (3)	1.376	100	1.91
bath towel	1.400	100	1.60
3 briefs	1.134	100	0.46
t-shirt -- dark grey	0.521	100	0.46
t-shirt -- 6 white	0.347	100	1.98
5 women white brief	0.660	100	0.52
hand towel	0.831	100	0.08
towel	0.862	100	0.23
bra small	0.770	100	0.10

In the following figures, the 100% cotton items are shown in red, the 0% cotton items are in blue, and the items that are a blend of cotton and synthetic content are shown in purple. The size of each bubble denotes the relative weight of each item in a given test load.

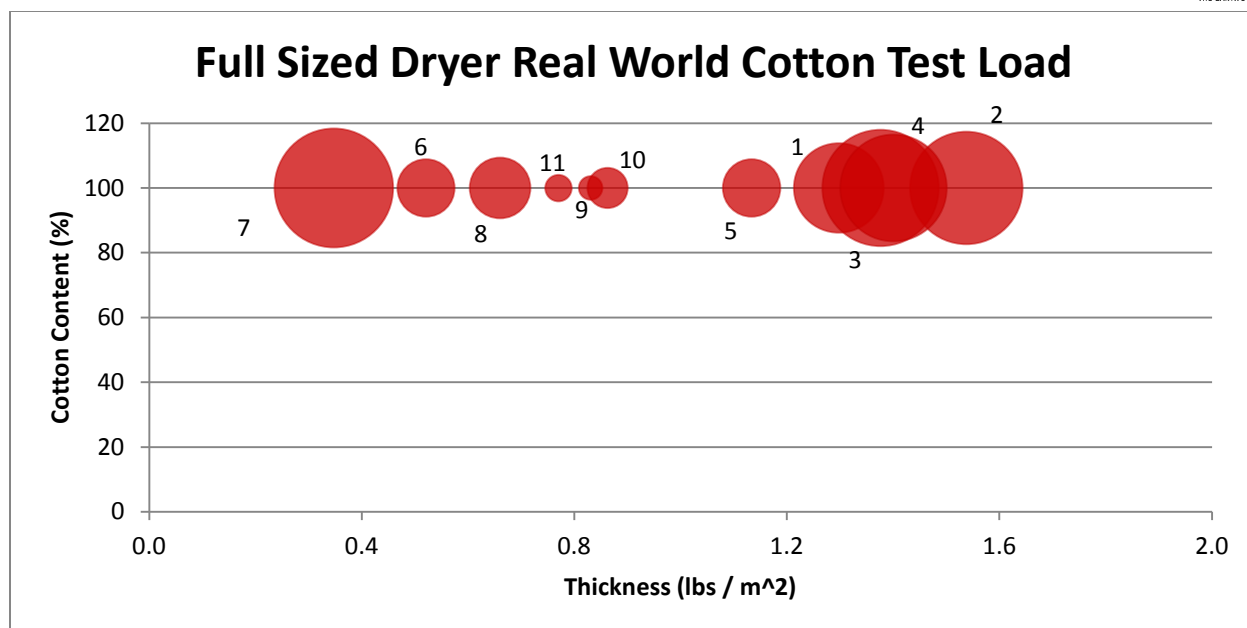


Figure 38. Full Size Dryer Real World Cotton Test Load including dark jeans, jeans 42x32, jeans 32x34, bath towel, 3 briefs; grey t-shirt, 6 white t-shirt, 5 white briefs, hand towel, towel, bra small

Table 11. Full Sized Dryer Real World 50-50 Test Load items, the approximate thickness of cloth, cotton content, and total weight of that item (may include multiple copies of an item e.g. 2 pairs of thin socks)

Item	Thickness (lbs/m ²)	Content (% cotton)	Weight (lbs)
black pants 2XL	0.709	0	0.91
black pants XL	0.667	0	0.82
2 boxer	0.320	55	0.29
checkered dress shirt	0.380	60	0.34
sheet set: flat sheet	0.272	60	1.37
sheet set: Std pillowcase	0.626	60	0.24
10 pair of socks-- thick	0.941	84	1.43
2 pair of socks-- thin	0.548	73	0.13

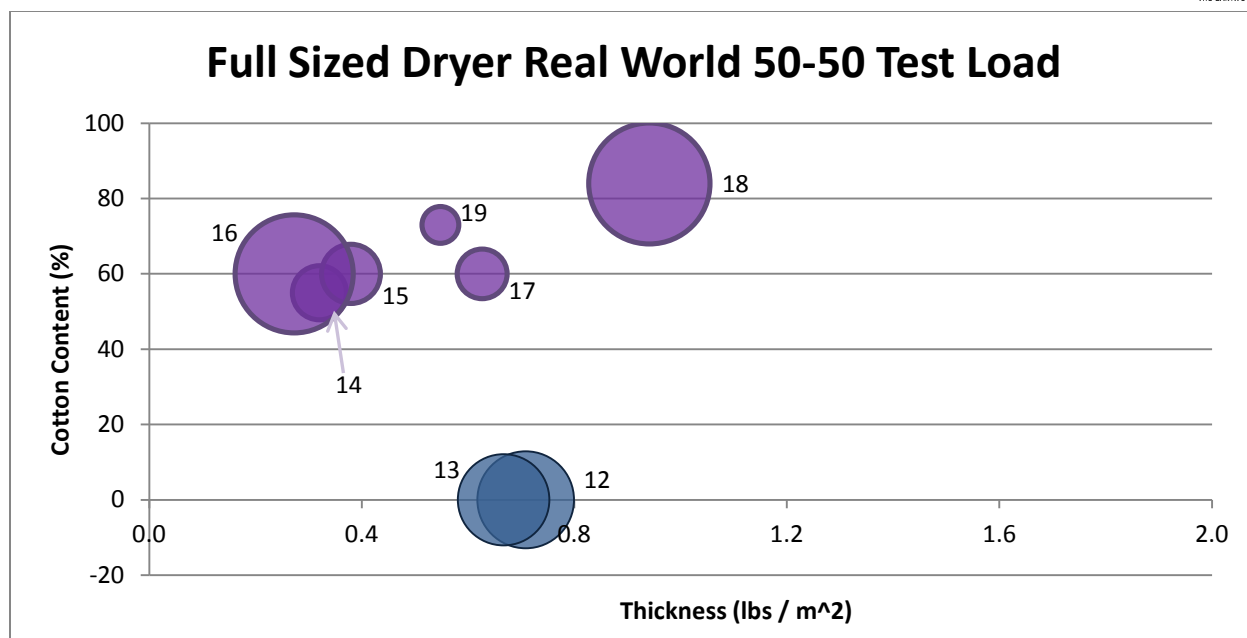


Figure 39. Full Size Dryer Real World 50-50 Test Load including black pants 2XL, black pants XL; 2 boxers, checkered dress shirt, sheet set (flat sheets, 1 pillowcase), 10 pairs thick socks, 2 pair thin socks

Table 12. Compact Dryer Real World Cotton Test Load items, the approximate thickness of cloth, cotton content, and total weight of that item (may include multiple copies of an item e.g. 3 women white brief)

Item	Thickness (lbs/m ²)	Content (% cotton)	Weight (lbs)
jeans 42x32 (3)	1.376	100	1.91
briefs	1.134	100	0.15
3 women white brief	0.660	100	0.31
tshirt--dark grey (1)	0.521	100	0.46
tshirt--white (2)	0.347	100	0.33

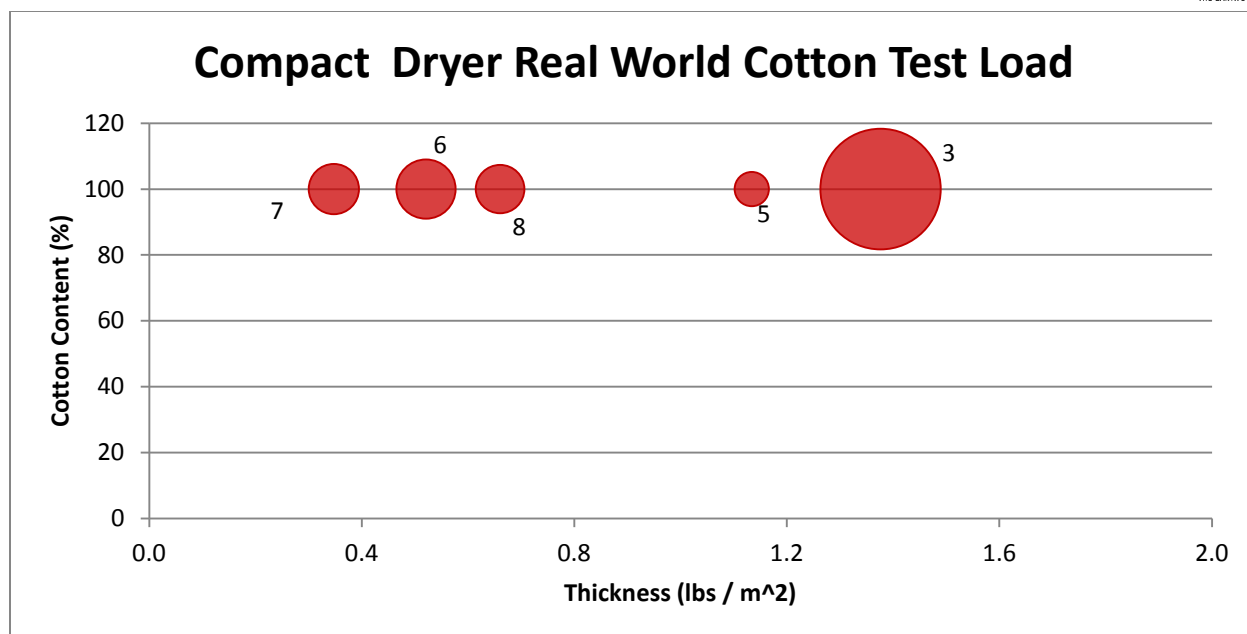


Figure 40. Compact Dryer Real World Cotton Test Load including jeans 42x32, brief, 3 white briefs, grey t-shirt, 4 white t-shirt

Table 13. Compact Dryer Real World 50-50 Test Load items, the approximate thickness of cloth, cotton content, and total weight of that item (may include multiple copies of an item e.g. 2 pairs of thin socks)

Item	Thickness (lbs/m ²)	Content (% cotton)	Weight (lbs)
swim trunks	0.719	0	0.34
bra large	0.943	0	0.13
2 boxer	0.320	55	0.29
checkered dress shirt	0.380	60	0.34
3 pairs of socks-- thick	0.941	84	0.43
pair of socks-- thin	0.548	73	0.03
sheet set: 2 Std pillowcases	0.626	60	0.49

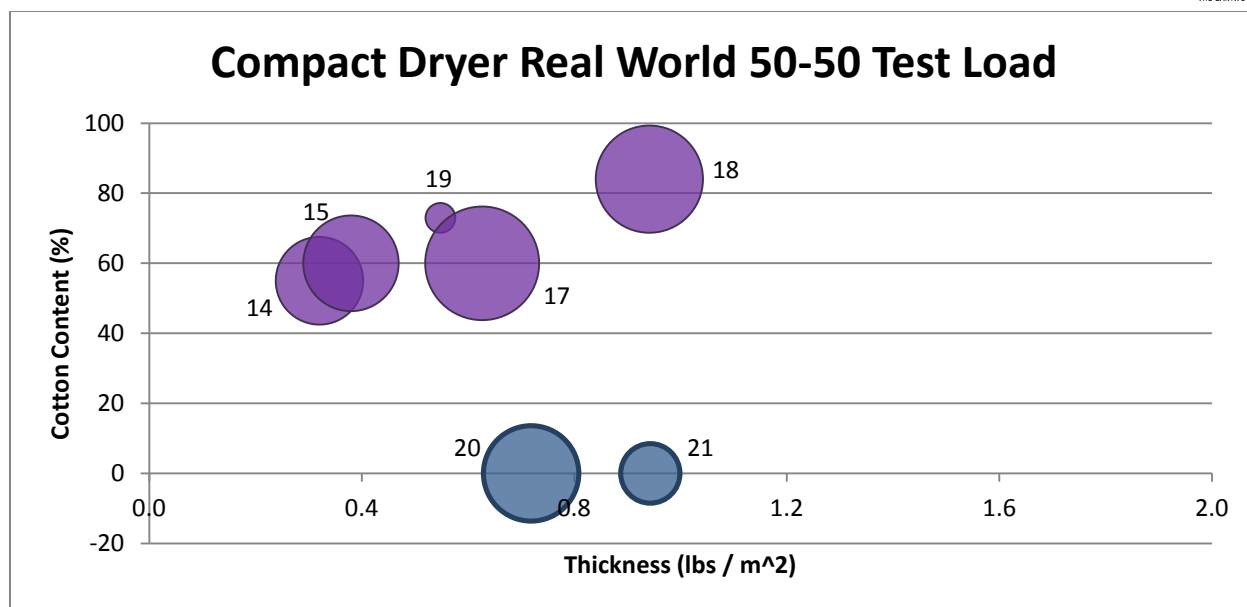


Figure 41. Compact Dryer Real World Cotton Test Load including swim trunks, large bra, 2 boxers, checkered dress shirt, 3 pair thick socks, 2 pillowcases, 1 thin sock

Table 14. Legend for figures above including items used in RW test loads.

No.	Item	No.	Item
1	Sweatshirt	16	Large bra (2)
2	Jms pants	17	Pair of socks-- thick
3	Dark jeans (1)	18	Pair of socks-- thin
4	Jeans 34x30 (2)	19	T-shirt--dark grey (1)
5	Jeans 42x32 (3)	20	T-shirt--white (2)
6	Shorts	21	Sheet set: flat sheet
7	Bath towel	22	Sheet set: fitted sheet
8	Towel	23	Sheet set: Std pillowcase (each)
9	Long pants, dune size 14 (2)	24	Black pants 2XL
10	Swim trunks	25	Black pants 2XL (lighter)
11	Checkered dress shirt (1)	26	Green reversible jacket (1)
12	Hand towel	27	Indigo reversible jacket (2)
13	Boxer	28	Black pants XL
14	Briefs	29	Women white brief
15	Small bra (1)		

Validating Testing

There were a number of instances when we were outside the tolerances of the 2011 DOE test procedure, but we still tried to validate our data with existing data in the California data set.

We will use uncertainty to mean plus or minus, and bias to mean a consistent offset of a parameter, like altitude (no DOE requirement), energy content in natural gas, ambient relative humidity, natural gas pressure, voltage, and (washer) rinse temperature. We estimated that our biases would cause us to measure the correct efficiency for the electric dryers and 6% higher efficiency for natural gas. The total uncertainty was ~4%. We compared our measured EF with the old DOE test procedure with published values in the California database for three dryers (see Table 15). Our measured efficiency was much lower than expected for the dryer that was efficient according to the California database. The DOE also measured dryers that were supposed to be higher efficiency according to the California database, and found that they were not higher efficiency, so this result is consistent. The other two dryers were about 6% less efficient than expected. This would be consistent with altitude decreasing efficiency by 4% instead of increasing efficiency by 2% as we assumed. We had less uncertainty in the estimate of the other biases. Regardless, we expect that our comparisons between dryers can be extrapolated to other conditions.

Table 15. Validation of efficiency tests using the Old DOE Test Procedure.

Old DOE Tests Dryer	CA Database EF	Gas + Electricity Combined	% Difference	
		EF Adjusted for Automatic Termination Field Use Factor = 1.04	CA: Adjusted	Expected
Electric entry-level	3.1	2.90	-6.5%	0.00%
Electric high efficiency	3.7	3.18	-13.9%	0.00%
Gas middle of line	2.8	2.79	-0.2%	6.00%

Airflow and Moisture Removed

We monitored the relative humidity of the dryer exhaust both directly and indirectly through the wet bulb and dry bulb temperature measurements. The indirect measurements were more accurate.

We assumed that the pressure of Durango, Colorado was 0.79 atm. We measured the ambient conditions only directly. We calculated the vapor pressure of water vapor with a modified Clausius-Clapeyron equation, which has less than 1% error over the range of interest. We then used the ideal gas law to convert this vapor pressure to grams of water vapor per cubic foot. We calculated the grams of dry air per cubic foot using the ideal gas law with the atmospheric pressure minus the vapor pressure. From this, we calculated a humidity ratio (grams of water per grams of dry air). We used a similar process to find the humidity ratio of the wet bulb exhaust condition. Using the

difference between the wet bulb and dry bulb and an assumption of the specific heat of moist air, we then calculated the amount of water that must have been evaporated going from the dry bulb to the wet bulb. We subtracted this amount of water from the wet bulb condition to find the dry bulb humidity ratio. Next we subtracted the ambient humidity ratio from the dry bulb exit humidity ratio to find the amount of water removed from the clothing per cubic foot. Finally, we multiply by the flow rate in cubic feet per minute to find the grams of water removed from the clothing per minute and converted this to ounces of water removed per minute.

The turbine type air flow meter finds the air velocity. The simple assumption is that that velocity applies to the entire pipe cross sectional area. However, the flow meter itself blocks about 25% of the area, and the flow near the pipe walls would be lower, so we estimate that the actual flow rate is only two-thirds as large as the simple calculation. The agreement between the calculated and measured water removal is only within a factor of two, so the water removal lines on the time series graphs should be taken more qualitatively.

Additional uncertainty in the multi-line graphs presented in the Results section may be due to the fact that the gas meter does not have an internal clock. This prevented us from exactly matching up measurements made on the other equipment, mainly temperature, exhaust air flow, remaining humidity, and electric power use, to the instantaneous gas flow.