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Clothes Dryer Automatic Termination Evaluation

Volume 2: Improved Sensor and Control Designs

September 2014

W TeGrotenhuis, Ph.D.

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory
Richland, Washington 99352

Executive Summary

Many residential clothes dryers on the market today provide automatic cycles that are intended to stop when the clothes are dry, as determined by the final remaining moisture content (RMC). However, testing of automatic termination cycles has shown that many dryers are susceptible to over-drying of loads, leading to excess energy consumption. In particular, tests performed using the DOE Test Procedure in Appendix D2 of 10 CFR 430 subpart B have shown that as much as 62% of the energy used in a cycle may be from over-drying. Volume 1 of this report shows an average of 20% excess energy from over-drying when running automatic cycles with various load compositions and dryer settings. Consequently, improving automatic termination sensors and algorithms has the potential for substantial energy savings in the U.S.

Here, the potential for saving energy through the reduction of over-drying has been demonstrated using low-cost humidity sensors to augment automatic termination algorithms of one standard electric and one standard gas dryer that are currently equipped with only thermistors and contact moisture sensors. Sensors priced at less than $4 when purchased in bulk were installed in the exhaust ducts of the dryers. A new algorithm was developed using humidity sensor measurements and used to augment the existing termination algorithms used by the dryers. Tests were performed with five test loads of varying composition over a wide range of load size using both high and medium temperature cycles. Using the humidity sensor, the new algorithm stopped the electric dryer earlier in 5 of 8 tests performed, producing 8-24% energy savings in those 5 tests while meeting final load dryness (i.e., final RMC) thresholds. Only one test had a significantly higher final RMC than the same test without the new algorithm, although the final RMC was still below 5%. The new algorithm stopped the gas dryer earlier in 4 of 8 tests, with a range of 5-8% energy savings, again without impacting final load dryness. In general, the algorithm was successful in saving energy with smaller loads and loads of more uniform composition, which is consistent with previous over-drying studies.

The results show there is potential for significant energy savings with residential clothes dryers by using low-cost humidity sensors to improve automatic termination. The effort did not attempt to optimize energy savings, which is most likely achieved by integrating this new approach with humidity sensors into existing termination algorithms that rely on thermistor and contact moisture sensors. If successful, energy savings significantly exceeding those achieved here are anticipated. The effort also did not address sensor reliability or durability, including susceptibility to lint fouling—these factors are left to the commercial product developers.

Acknowledgements

Many thanks to those who contributed to accomplishing the work reported in this document. Richard Pratt with assistance from Nicole Stanton led the effort to acquire data from the existing sensors; procure and install the humidity sensors; and accomplish other electrical engineering tasks such as installing power supplies to stabilize voltage. Vinh Nguyen performed the majority of the dryer testing with assistance from Kevin Gervais and Jacob Fricke. Austin Winkelman, Gregory Carter, Randal Berg, and Dave Winiarski helped to establish the testing facility and install all the necessary equipment and services to perform testing according to the DOE test procedures. Dustin Caldwell and Jair Lizarazo-Adarme created the data acquisition and control system and implement the new automatic termination algorithm. Dennis Stiles and Dale King provided programmatic support. Also, thanks to James Battaglia and Constantin von Wentzel of Navigant for their helpful consultation and recommendations of low-cost humidity sensors.

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1.0 Introduction

1.1 Objective

The goal of this study was to demonstrate the use of low-cost humidity sensors to improve automatic termination cycles of residential clothes dryers. Past dryer testing has shown excess energy consumption of up to 62% due to over-drying [1] with automatic termination settings. The results reported in Volume 1 confirmed these findings by evaluating the percentage of energy expended after loads of varying composition reached target final remaining moisture content (RMC) levels of 5% and 2%, two thresholds used for concluding that a load is dry. On average, in excess of 20% of the total energy was consumed after the clothes were dry. The objective of this study is to augment the thermistors and contact moisture sensors currently used by automatic termination algorithms with additional humidity sensor technology that can improve the accuracy and consistency of the algorithms used for automatic termination.

Humidity sensors providing RH and temperature measurements were installed in the exhaust ducts of two standard residential clothes dryers, one electric and one gas, and an algorithm was developed for automatically terminating cycles using the measurements. The algorithm was overlaid on existing termination algorithms of the dryer so that either could end a cycle. A set of tests were performed with loads of varying size and composition to demonstrate the effectiveness of the new algorithm in saving energy by reducing over-drying, while still meeting industry standards for final dryness. The objectives did not include long-term durability or reliability, such as lint fouling susceptibility, nor considerations of all possible operating scenarios. The goal was to create the impetus for manufacturers to pursue implementation of new technology that will save energy in future products.

1.2 Background

Historically, clothes dryer energy conservation standards have focused on the bulk drying phase by manually terminating tests when the DOE test load reaches between 5% and 2.5% RMC before entering the cool down phase [1]. Test procedures for measuring dryer energy factor (EF) have applied a field-use factor to account for the additional energy used after the end of the test to the end-of-cycle. Many dryer models have automatic termination cycles that use sensors to detect load dryness and determine when to stop the cycle. These sensors are typically thermistors measuring air temperature entering or leaving the drum or contact moisture sensors. Contact moisture sensors detect the moisture content of cloth touching the sensor. During the high-heat phase—after the bulk drying phase and before the cool down phase—of automatic termination cycles, the dryer controls determine when the load is dry and when to end the cycle. Currently, applying a constant field-use factor, rather than testing to the end-of-cycle, does not account for the effectiveness of the termination controls, so over-drying does not affect measured EFs.

The efficacy of a dryer's control program at determining when the load is dry impacts consumer experience in addition to the energy use of the appliance. If the cycle ends too soon, the user experiences a partially wet load and may choose to not use automatic cycle settings, which could lead to higher energy consumption. Although not necessarily perceived by the consumer, if the control program prolongs the cycle, energy is expended unnecessarily, and the load may continue being heated at higher temperatures for longer times.

The DOE issued a Final Rule on August 14, 2013 [2] that included a new optional procedure for clothes dryer testing (Appendix D2 of 10 CFR 430 subpart B) [3]. The new procedure specifies using automatic termination settings if available, and running the cycle to the end-of-cycle. This includes the energy consumed by the dryer after the load reaches 2% RMC until the end-of-cycle in the EF calculation. Because the existing D1 procedure applies a field-use factor of 1.04 for dryers equipped with automatic termination, if the total energy used by a dryer in the D2 test (that runs to end-of-cycle) exceeds the total energy used during the D1 test (that stops the cycle between 5% and 2.5% RMC) by at least 4%, EFs will be lower with the revised procedure.

Energy consumed by the heaters and motor after a load is dry represents inefficiency and an opportunity for energy savings. Past dryer testing has shown extensive over-drying of DOE test loads [1]. Test data have shown that energy consumption can be 11–72% greater than that required to dry a DOE load to 5% RMC, and 4–62% greater than that required to reach 2% RMC [1]. Therefore, dryers currently on the market typically consume more than 4% of the total energy of the drying cycle after the load is dry, so EFs will be lower with the revised test procedure that allows automatic termination cycles to run to end-of-cycle.

Excess energy consumption from over drying represents a significant opportunity for improving the energy efficiency of residential clothes dryers. By transitioning to a test procedure that accounts for all of the energy used during the automatic termination cycle, such as the new D2 procedure, manufacturers would be incentivized to improve their automatic termination cycles.

1.3 Test Procedures

Test results were obtained using the test procedure in Appendix D2 of Subpart B of 10 CFR Part 430 (D2 procedure), which was added to the Test Procedures for Residential Clothes Dryers in the August 14, 2013 Final Rule [1]. The D2 procedure is currently optional and may be used early to show compliance with the January 1, 2015 standards. Details of the installation and set-up, bone drying procedure, dryer and test load preparations, running of the tests, and data acquisition and calculations are provided in Volume 1 of this report. The scope of this project is to focus on the energy use of automatic cycles. Consequently, results are reported for EF; results were not obtained for combined energy factors (CEF) which includes energy consumption during standby or off-mode nor drum capacity.

Testing was performed with the standard DOE test loads [3], the Association of Home Appliance Manufacturers (AHAM) Standard HLD-1-2009 test loads (AHAM 2009) [4], and the AHAM Standard HLD-1-1992 test loads (AHAM 1992) [5]. The DOE loads that are used in both the D1 and D2 procedures are very uniform, consisting of a single cloth type composed of 50/50 cotton and polyester and of uniform cloth ply and dimensions. The AHAM 2009 load is a mixture of cotton bed sheets, pillow cases, and towels, which are more varied in cloth ply and a larger range of cloth sizes. The AHAM 1992 load is the most varied in cloth size and composition and is more similar to typical laundry because it uses items of actual clothing with different fabrics and varying thicknesses. In addition, testing was performed with a 3-pound extreme light load and a 16.9-pound extreme heavy load. The 3-pound AHAM 1992 load was selected as the extreme light load for a standard dryer, and the combination of the 8.45-pound DOE load and the 8.45-pound AHAM 1992 was selected for the extreme heavy load. While not intended to be comprehensive, these loads provided results for loads of varying composition and size.

A standard electric vented dryer and standard gas dryer were selected for this investigation, and were equipped with humidity sensors and operated according to a new automatic termination algorithm. The standard electric dryer was the same as Test Unit 1 in Volume 1, which was a 7.0-cubic-foot vented front-load dryer with automatic cycle settings that allow for a choice of 17 cycles. The dryer was equipped with dual thermistor sensors and a contact moisture sensor located at the front of the drying compartment near the door. The gas dryer was the same as Test Unit 4 in Volume 1, which was a 7.3-cubic-foot front-load gas dryer with 10 selections for sensor dry cycles and additional adjustable temperature, dryness, and other settings. Unit 4 was equipped with one thermistor and a contact moisture located at a fixed location in the drying compartment. The same Test Unit designation are used here for consistency. Dryer settings were selected following the D2 procedure, which prescribes the Cottons or Normal cycle setting at the highest temperature setting and normal dryness level. If the final RMC was greater than 2% for the DOE loads or greater than 5% for the AHAM loads, the test was rerun at the highest dryness setting. Additional tests were performed using the medium temperature settings for comparison. Results reported in Volume 1 are used as the baseline performance for the dryers tested in this effort.

2.0 Concept and Approach

Low-cost humidity sensors were procured and installed in the dryer exhaust ducts near the suction of the air blower to monitor the temperature and relative humidity of the exhaust, which are used to calculate the water content of the air being exhausted from the dryer. The proposed concept is to use this information in automatic termination algorithms in order to more accurately stop drying cycles when the load is dry, thereby preventing over-drying and saving energy. Not only would this improve the energy efficiency of dryers, but it would also reduce the exposure of clothes to high temperatures that can contribute to wear.

Low-cost, compact humidity sensors have recently come on the market that can be purchased with shields for protecting the sensor, such as from lint fouling. Three different sensors were procured and installed for side-by-side comparison of their performance in the exhaust of clothes dryers. Testing was performed to investigate how these sensors could be used to improve automatic termination algorithms as well as the resulting potential for energy savings while still meeting industry standards for load dryness.

The demonstration was performed with two commercially-available, standard-size residential clothes dryers that were previously found to over-dry loads as reported in Volume 1. The demonstration did not include long-term durability testing, such as determining the susceptibility and effects of lint accumulation on sensor performance, nor did it address all operating scenarios, such as the user interrupting the dryer operation in the middle of a cycle. These issues are important but left to the implementation of the concept in commercial products.

2.1 Dryer Energy Use and Water Removal Rate

A vented clothes dryer pulls in air from the room where the dryer is located, which can be at varying temperature and relative humidity. The dryer then heats the air before passing it through the drum containing the wet load, and typically exhausts the air to the outdoors. When a cycle starts, most of the energy is used to heat up the wet load, the heating elements, and the rest of the dryer. The beginning warm-up stage of a typical drying cycle is indicated in Figure 2.1. Next, during the bulk drying stage, the exhaust gas temperature normally stabilizes, the heaters are normally on continuously, and the exhaust air is at high relative humidity. During this stage, most of the heat duty goes to the latent heat of evaporating water from the load.

As the drying rate decreases, the latent heat duty also decreases, causing a shift to sensible duty, which begins raising the drum temperature and the exhaust air temperature, as shown for a sample cycle in Figure 2.1. The cycle transitions to the high heat stage, at which point dryers typically cycle the heating elements or gas burner off and on to prevent overheating of the load while the drum continues rotating, which is observed in the power profile in Figure 2.1. For automatic drying cycles, the dryers use thermistors and/or contact moisture sensors to detect when the load is dry. The final stage is cool down, in which the dryers continue blowing air through and rotating the drum with no heating for typically 4-5 minutes (not delineated in Figure 2.1). The RMC data calculated from the scale measurements are also included in Figure 2.1. The increase in RMC during the cool-down phase is indicative of over-drying during the high heat stage.

The standard electric dryer tested has two resistive heating elements powered with 240V electricity. Each element can be turned on and off independently for three levels of power—both off or one or two elements on—and each consumes almost 3 kW of power when on. The standard gas dryer uses a single natural gas burner to heat the air before entering the drum, which is turned on and off to control heating. The burner uses the equivalent of about 7 kW of power when gas flow rate is converted to power using the gas heating value, which is done for the EF calculations and energy use analyses.

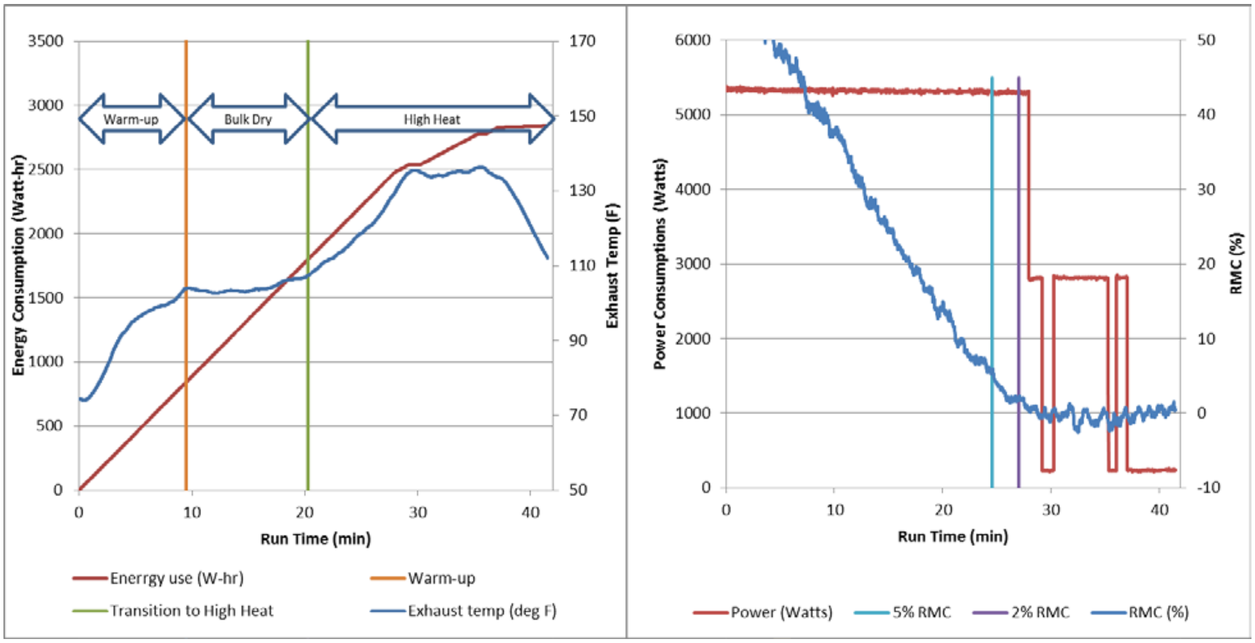


Figure 2.1. Example of warm-up, bulk dry, and high heat (combined with cool down) stages of an automatic termination cycle from testing of Test Unit 1 with the AHAM 1992 load on COTTONS and high temperature settings. The power profile on the right shows when one or both heating elements are on along with the RMC data obtained from the scale measurements.

In earlier testing, a humidity probe was inserted into the exhaust air to monitor relative humidity and temperature. This probe was used to collect the temperature data shown in Figure 2.1. The probe also typically showed a rapid increase in RH during the warm-up phase to between 80% and 100%, which was either maintained or gradually decreased through the bulk drying phase. However, when the cycle entered the high heat stage, the RH typically declined rapidly. The consistency of the behavior with different automatic cycle dryer settings, as well as between different dryers, gave rise to the idea that a humidity sensor could be used to improve the accuracy of automatic termination algorithms.

One method for detecting when water is being added to the air flowing through the drum is to compare the water concentration in the exhaust to the water concentration of the incoming ambient air. Water concentration is calculated from the RH sensor measurements using Dalton's law and the definition of relative humidity:

$$y_{H_2O} = \frac{RH \cdot P_{sat}^{\mathrm{H_2O}}(T)}{P} \tag{1}$$

where P_{sat} is the saturation pressure of water at temperature, T, and P is the total pressure.

The ratio of the exhaust water concentration to that of the ambient air is used to define the Water Removal Rate (WRR) parameter:

$$WRR = \frac{y_{H_2O,\text{exhaust}}}{y_{H_2O,\text{intake air}}} - 1 = \frac{RH_{\text{exhaust}} \cdot P_{sat}^{H_2O}\left(T_{\text{exhaust}}\right)}{RH_{\text{ambient}} \cdot P_{sat}^{H_2O}\left(T_{\text{ambient}}\right)} - 1 \qquad (2)$$

The number 1 is subtracted from the ratio so that when WRR>0, the moisture content of the air is increasing going through the drum, which indicates active drying. When WRR<0, moisture is being removed from the air and possibly into the clothes, which can happen when the load cools after over drying.

The WRR parameter indicates when water is being added to or removed from the air passing through the drum, regardless of the ambient temperature and humidity. This is necessary to be effective at all ambient conditions. However, all tests were performed at the D2 ambient air test conditions of 75 ± 3ºF and RH at 50 ± 10%.

During the earlier testing reported in Volume 1, a second RH probe was installed in the chamber where the dryers were located. The combination of the exhaust air RH probe and the ambient RH probe provided each of the quantities needed to calculate WRR from Equation 2. Water saturation pressure was calculated from the measured temperature using a correlation. Figure 2.2 shows the WRR profile corresponding to the example cycle given in Figure 2.1. In this case, the WRR parameter crosses zero at approximately 30 minutes, which indicates the load is dry according to the theory. After 30 minutes, further heating is unnecessary and lowers dryer efficiency.

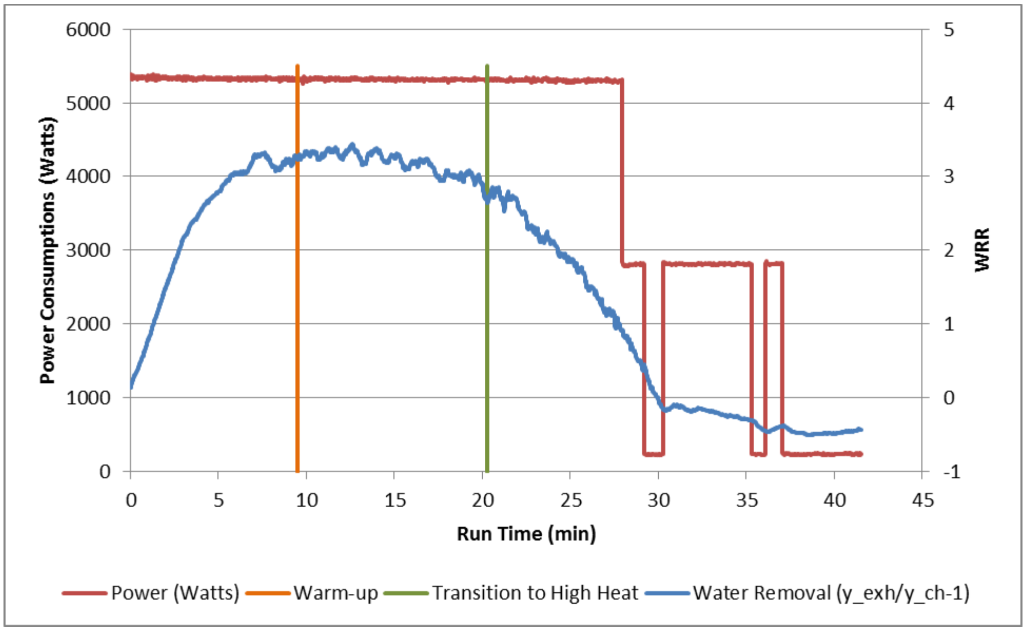


Figure 2.2. Power consumption and water removal rate (WRR) of an automatic termination cycle from testing of Test Unit 1 with the AHAM 1992 load on COTTONS and high temperature settings.

2.2 Sensor Equipment

The probes used to measure the RH and temperature of exhaust air and the chamber are laboratory instruments that are too costly and not suitable for use in commercially-available residential clothes dryers. Instead, three low-cost RH sensors were procured and installed inside dryers in the exhaust ducting near the suction of the blower. These sensors were mounted to a circuit board that was attached to the wall of the ducting between the lint filter and the intake of the blower. The board was attached using sheet magnets with an adhesive backing or with Velcro. It is anticipated that other installation options are preferred, such as locating the sensor in the wall of the blower housing where higher shear forces will protect the sensor from lint fouling; this is where thermistors and thermostats are placed by some manufacturers. Since lint fouling and long-term durability were not considerations in this effort, the sensors were placed in more convenient locations, and wires connecting to the sensors were run under the lint filter through the edge of the door to the data acquisition and control system.

Table 2.1. Humidity Sensors Bill of Materials

Part #	Description	Price each	Price ea., 2.5k qty	Location
DHT11	Single Data Stream Humidity Sensor (1st generation)	$5.00		http://www.adafruit.com/products/386?gclid=CI-PwNTRrr4CFSgQ7AodJ2MAXQ
DHT11	Single Data Stream Humidity Sensor (1st generation)		$2.77	http://www.aliexpress.com/item/100-new-original-Large-quantity-please-contact-Dht11-digital-temperature-and-humidity-sensor-module-pdf/773972437.html
DHT22	Single Data Stream Humidity Sensor (2nd generation)	$9.95		http://www.adafruit.com/products/385?gclid=CJ7qvObRrr4CFcNj7AodjFwAkg
DHT22	Single Data Stream Humidity Sensor (2nd generation)		$3.43	http://www.aliexpress.com/item/With-optocoupler-4-channel-4-channel-relay-modules-relay-control-panel-PLC-relay-5V-four-way/1580326097.html
Si7021-A10-GM	I^2C Data onboard Humidity Sensor (Base unit)	$3.88		http://www.digikey.com/product-detail/en/SI7021-A10-GMR/336-2543-1-ND/4211734
Si7021-A10-GM	I^2C Data onboard Humidity Sensor (Base unit)		$3.52	http://www.digikey.com/product-detail/en/SI7021-A10-GMR/336-2543-2-ND/4211762
Si7021-A10-GM1	I^2C Data onboard Humidity Sensor (Shielded unit)	$4.27		http://www.digikey.com/product-detail/en/SI7021-A10-GM1R/336-2542-1-ND/4211738
Si7021-A10-GM1	I^2C Data onboard Humidity Sensor (Shielded unit)		$3.88	http://www.digikey.com/product-detail/en/SI7021-A10-GM1R/336-2542-2-ND/4211753

The three sensors that were used in the study are the DFRobot DHT11 Temperature and Humidity Sensor (DHT11), the MaxDêtect DHT22 Humidity Sensor (DHT22), and the Si7021-A10 Sensor implemented on an I^2C Data onboard (I2C). Information for each of the sensors is provided below, and prices for each sensor are provided in Table 2.1. The purpose of installing and testing three sensors was to evaluate and compare the performance of multiple low-cost sensors, although only one sensor was used in the revised termination algorithms, as discussed below.

2.2.1 DHT11 Temperature and Humidity Sensor

The DFRobot DHT11 Humidity Sensor is a temperature and humidity sensor with a calibrated digital signal output. This sensor includes a resistive-type humidity measurement component and an NTC temperature measurement component. It connects to a high-performance 8-bit microcontroller to give fast response, anti-interference, and cost effectiveness. A picture of the sensor and its dimensions are provided in Figure 2.3.

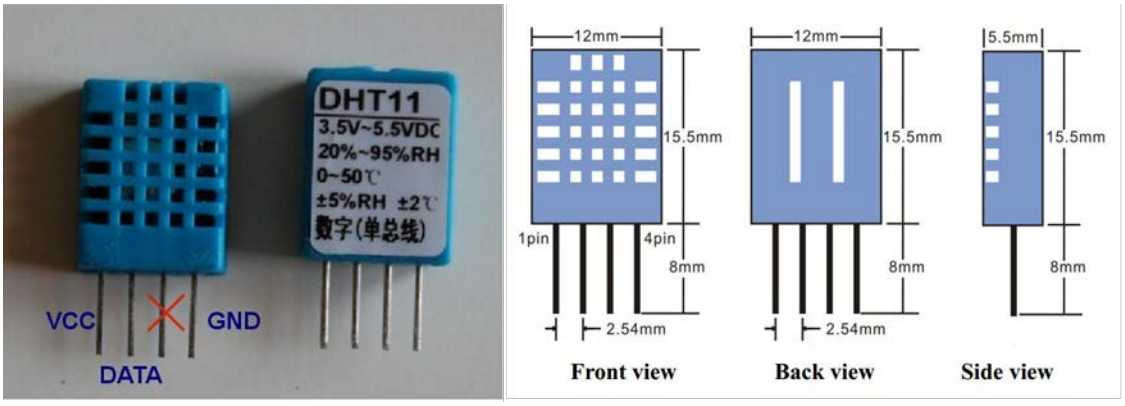


Figure 2.3. Picture and physical dimensions of the DHT11 humidity sensor

Technical specifications from the product literature of the DHT11 are provided in Table 2.2. The measurement range of the sensor is only 20-90% RH and 0-50°C. Operating conditions in the exhaust ducts will be outside this measurement range, based on previous exhaust measurements. In addition, there is concern whether the sensor is susceptible to damage when exposed to temperatures higher than its measurement range. This sensor also has relatively low accuracy (only ±5% RH and ±2°C), and has a slow response (as long as 30 seconds). However, the sensor is the lowest cost option in quantity, at $2.77 each in quantities of 2,500, so it was included in the testing.

Table 2.2. Technical Specifications and Electrical Characteristics of the DHT11 Humidity Sensor

Item	Measurement Range	Humidity Accuracy	Temperature Accuracy	Resolution	Package
DHT11	20-90%RH 0-50 ℃	±5%RH	±2℃	1	4 Pin Single Row

Parameters	**Conditions**	**Minimum**	**Typical**	**Maximum**
Humidity				
Resolution		1%RH	1%RH	1%RH
			8 Bit	
Repeatability			±1%RH	
Accuracy	25℃		±4%RH	
	0-50℃			±5%RH
Interchangeability	Fully Interchangeable			
Measurement Range	0℃	30%RH		90%RH
	25℃	20%RH		90%RH
	50℃	20%RH		80%RH
Response Time (Seconds)	1/e(63%)25℃, 1m/s Air	6 S	10 S	15 S
Hysteresis			±1%RH	
Long-Term Stability	Typical		±1%RH/year	
Temperature				
Resolution		1℃	1℃	1℃
		8 Bit	8 Bit	8 Bit
Repeatability			±1℃	
Accuracy		±1℃		±2℃
Measurement Range		0℃		50℃
Response Time (Seconds)	1/e(63%)	6 S		30 S

VDD=5V, T = 25℃ (unless otherwise stated)

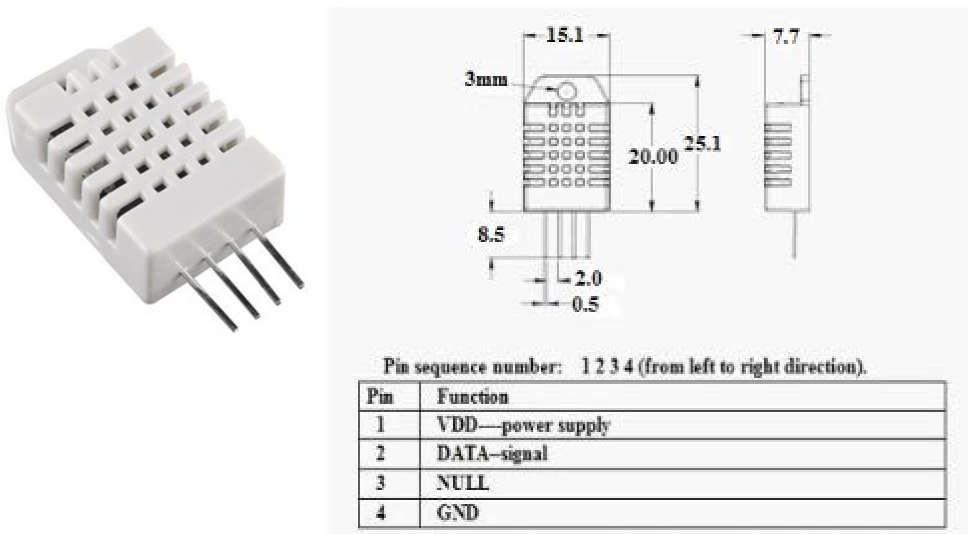
	Conditions	Minimum	Typical	Maximum
Power Supply	DC	3V	5V	5.5V
Current Supply	Measuring	0.5mA		2.5mA
	Average	0.2mA		1mA
	Standby	100uA		150uA
Sampling period	Second	1		

Note: Sampling period at intervals should be no less than 1 second.

2.2.2 DHT22/RHT03 Temperature and Humidity Sensor

The MaxDêtect DHT22 Humidity Sensor uses an output calibrated digital signal that detects both humidity and temperature. The sensing elements are connected to the MSP430F2274 by an 8-bit single-chip computer that translates the sensor output into a 40-bit binary code. While the specifications indicate that it will operate with voltages as low as 3.3V, literature suggests that using a minimum voltage of 5V will improve reliability and stability significantly.

The sensor is pictured in Figure 2.4, along with a schematic with dimensions. Technical specifications from the product literature are provided in Table 2.3. In contrast to the DHT11, the DHT22 operates over the full RH range and up to 80°C, which is considerably higher than temperatures previously measured in the exhaust from dryers. The DHT22 is also more responsive than the DHT11, with the ability to interrogate the sensor at 0.5 Hz. This second generation sensor is slightly more costly in quantity, at $3.43 each in quantities of 2,500.



Pin	Function
1	VDD—power supply
2	DATA–signal
3	NULL
4	GND

Figure 2.4. Picture and physical dimensions of the DHT22 humidity sensor

Table 2.3. Technical Specifications of the DHT22 Humidity Sensor

Model	RHT03	
Power supply	3.3-6V DC	
Output signal	digital signal via MaxDetect 1-wire bus	
Sensing element	Polymer humidity capacitor	
Operating range	humidity 0-100%RH;	temperature -40~80Celsius
Accuracy	**humidity +-2%RH**(Max +-5%RH);	temperature +-0.5Celsius
Resolution or sensitivity	humidity 0.1%RH;	temperature 0.1Celsius
Repeatability	humidity +-1%RH;	temperature +-0.2Celsius
Humidity hysteresis	+-0.3%RH	
Long-term Stability	+-0.5%RH/year	
Interchangeability	fully interchangeable	

2.2.3 Si7021-A10 Temperature and Humidity Sensor

Silicon Labs' Si701x/2x sensors combine humidity and temperature sensor elements with an analog-to-digital converter, signal processing, and an I2C host interface. Low-K polymer dielectrics are used to achieve high accuracy and long term stability, along with low drift and low hysteresis. Product documentation claims the lowest power consumption in the industry for a relative humidity and temperature sensor, along with full factory calibration. For protection against dust, dirt, and chemical contaminants during PCB reflow as well as device operation, the sensor can be fitted with an optional factory-installed cover. The sensor is shown in Figure 2.5. The dimensions are 3 mm x 3 mm x 0.75 mm. The list in Figure 2.6 gives technical specifications for the sensor. The operating range is the full 0-100% RH and up to 125°C, which is higher than either of the other two sensors. The sampling time is less than 1 second. However, product literature states that response time[1] for a step change in RH is typically 18 seconds and 5.1 seconds for a step change in temperature. This sensor is the most costly in quantity, at $3.88 each for the shielded model in quantities of 2,500.

Figure 2.5. Pictures of the Si7021-A10 Humidity Sensor

Features

- Precision Relative Humidity Sensor:
  - Si7013/21: ± 3% RH (maximum) @ 0–80% RH
  - Si7020: ± 4% RH (maximum) @ 0–80% RH
- Temperature Sensor:
  - ±0.4°C accuracy (maximum) @ -10 to +85°C
- 0 to 100% RH operating range
- Up to -40 to +125°C operating range
- Wide operating voltage range (1.9 to 3.6 V)
- Low Power Consumption: 1.9μW average power at 3.3V and 1 sample per second
- I^2C host interface
- Integrated on-chip heater
- 3mm x 3mm DFN package
- Excellent long term stability
- Factory calibrated
- Optional factory-installed filter/cover
  - Lifetime protection during reflow and in operation
  - Protects against contamination from dust, dirt, household chemicals and other liquids
- AEC-Q100 automotive qualified

Figure 2.6. List of Si7021-A10 features and specifications from the product literature

[1] Response time for the I2C sensor is defined as the change in sensor output reaching 63% of the total step change in RH or temperature.

Concerns with the Si7021-A10 are that it is delicate and easily damaged, which was experienced in the process of installing and operating the sensor. The first sensor was not equipped with the shield that protects the sensor. A second sensor was installed that was equipped with the cover in later testing. For proper functioning, the sensor must be soldered to a board and cannot be free hanging.

2.3 Revised Termination Algorithms

Clothes dryers have evolved to where most models offer automatic termination cycles that use sensors and algorithms to determine when to stop the cycle based on load dryness. These sensors are typically contact moisture sensors or thermistors measuring air temperature entering or leaving the drum. Contact moisture sensors detect the moisture content of cloth touching the sensor. During the high-heat phase—after the bulk drying phase and before the cool down phase—the dryer uses proprietary algorithms to determine when the load is dry and when to end the cycle. Control systems also use the thermistors, as well as other thermostats, to protect the dryer and its contents from overheating.

The approach to revising the termination algorithms was to overlay additional logic on top of the dryer's existing termination algorithm. This is accomplished by adding relays to the wiring of the heating elements or gas burner that allow our control system to turn off heating of the drum air independently from the dryer's control system. Therefore, both the existing dryer control system and our control system must send signals to turn on the heaters, and the heaters turn off if signaled by either system. This allows the existing dryer termination algorithm, as well as the controls that prevent overheating, to function normally.

The revised algorithm that is tested here terminates the cycle when either the dryer's existing logic, or the new logic based on the WRR parameter, determines that the load is dry. This is the simplest approach for using humidity sensors to augment automatic termination algorithms. There is an opportunity to develop more complex algorithms that combine thermistor, moisture sensor, and humidity measurements, which may be more reliable and robust in stopping cycles when a load is dry while also ensuring industry standards for load dryness are met. Investigating more complex algorithms is beyond the scope of this effort.

The new algorithm using a humidity sensor in the exhaust duct includes the following four steps:

1. initialization of the WRR calculation,
2. a trigger that activates the algorithm,
3. the algorithm determines that the load is dry and turns off the heaters, and
4. completing the cycle.

The implementation of these steps is described in detail below.

2.3.1 Initialization of the WRR Calculation

Computing WRR using Equation 2 entails monitoring both the exhaust air and the ambient air, which requires two RH sensors. This doubles the cost of implementing RH sensors. In addition, the ambient air is not likely to change appreciably over the duration of a drying cycle, so continuous monitoring of ambient RH is superfluous. Alternatively, it may be possible to obtain the ambient RH and temperature at the start of the cycle using the exhaust RH sensor, which would allow the WRR to be implemented with only one sensor.

Three options were considered for initializing the WRR calculation at the start of a cycle using the RH probe located in the dryer exhaust duct. The first option, referred to as the 'soak' option, is to obtain the ambient water concentration before the cycle starts. The second 'cold start' option is to start operating the blower with the heaters off at the start of the cycle to move ambient air past the RH sensor and get a measurement of ambient water concentration. The third 'extrapolation' option collects water partial pressure data (y_{H2O} P calculated from Equation 1 using the RH sensor readings) as a function of time at the beginning of the cycle, and extrapolates back to zero time to get the ambient water content. All three options must handle a variety of real-world scenarios, such as consecutive cycles that start with a warm dryer or a cycle that is interrupted for some unknown period of time, which creates difficulties with methods that initiate the WRR calculation with one sensor in the exhaust duct. It is beyond the scope of this effort to demonstrate a robust algorithm for all scenarios; this is left to those implementing the concept in commercial products.

The second 'cold start' approach was tried using air dry cycles, and it was discovered that a wet load in the drum will immediately raise the RH of the air flowing through the drum, even with the heaters off. Subsequently, the 'extrapolation' method was used to illustrate that a single humidity sensor possibly can be used to implement the WRR algorithm, however, further investigation is needed to validate that this approach provides an accurate estimate of the WRR at the start of the test. The process is illustrated in Figure 2.7 using data from one of the sensors installed in Test Unit 1. The linear least squares fit of the first 30 seconds of data is shown in the plot, and the intercept of 1.5067 is used during the rest of the cycle in the denominator of Equation (2) to calculate WRR.

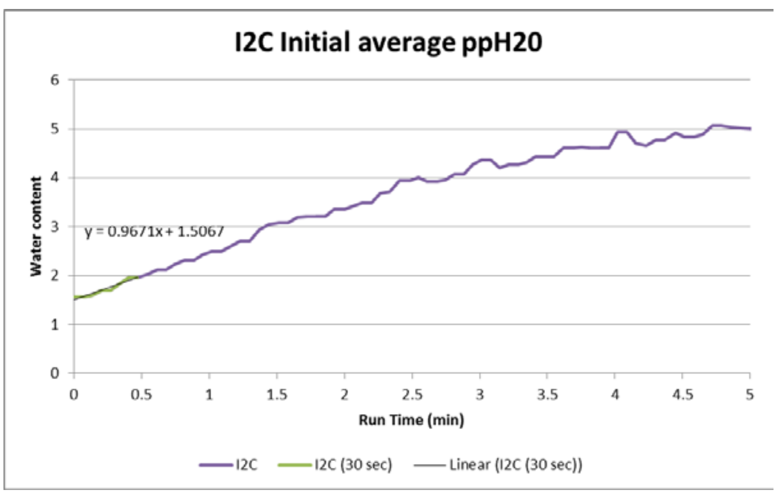


Figure 2.7. Example of obtaining a measure of the ambient water content by extrapolating the exhaust water content (water partial pressure) from the first 30 seconds of a drying cycle.

2.3.2 Activating the Algorithm

When a cycle first starts, the WRR algorithm is inactive and will not terminate the cycle until the WRR calculation is initialized and the algorithm is activated. An activation step is necessary because without this step, the low value of the WRR parameter early in the cycle would prematurely terminate the cycle. The WRR starts at a low value because there is relatively little evaporation of water during the warm-up stage while the load and dryer are initially being heated. This is seen in the example cycle shown above in Figure 2.2. Multiple options for activating the WRR algorithm were implemented, including setting minimum threshold values for the WRR and/or the exhaust temperature. For most tests, the WRR trigger was used to activate the algorithm. If a load is too small to ever generate a WRR above the trigger value, then the algorithm is never activated and cycle termination is only determined by the dryer's existing algorithm.

2.3.3 Determining When the Load is Dry and Turning Off the Heaters

A critical step in the algorithm is determining when the load is dry based on the WRR parameter. When the algorithm decides the load is dry, the heaters are turned off and the dryer continues to operate with the drum rotating and air flowing through the drum. The simplest logic is to base the decision on the WRR reaching a minimum threshold value. Selecting that value is very important because if the threshold is too high, the cycle will terminate prematurely with the load still wet. Setting the threshold too low will cause the cycle to continue with the heating elements operating after the load is dry and the algorithm will be ineffective in saving energy. Furthermore, the threshold must be universal across varying load compositions and sizes and ambient conditions, although investigating the latter was beyond the scope of this project.

A series of tests were performed using the D2 procedure and the 5 load types, and the data analyzed in order to choose the appropriate threshold for the WRR. The dryers were placed on a platform scale and the weight was recorded every second during the drying cycles. The scale weight was used to calculate the RMC of the test load during the cycle. Volume 1 of this report provides more information on how RMC was obtained and the method used to determine when the load was dry. For each preliminary test, a WRR threshold was selected that would have stopped the dryer when the load was dry. The threshold selected for the WRR algorithm was generally the minimum value of those compiled from tests with varying load sizes, compositions, and dryer settings. Selecting the minimum value ensures the algorithm consistently allows cycles to reach standards for dryness. Specific threshold values for each dryer are discussed below in Section 3.0.

The simple threshold logic was not sufficient for the gas dryer. Combustion of natural gas produces water, which increases the WRR value. Therefore, the WRR drops precipitously when the dryer turns off the gas burner, which causes the WRR to reach its threshold value too soon and turns the dryer off too soon. Consequently, the algorithm was modified for the gas dryer. Once the gas dryer went into the high heat stage of the cycle, the WRR peaks occurred at the moment the dryer's control system turned the burner off to prevent overheating. The rest of the time, the WRR was either decreasing when the burner was off or increasing when the burner was on. Therefore, the algorithm only checked whether the WRR had reached its threshold when the dryer's control system turned the burner off.

It is anticipated that more complex algorithms will be developed that take advantage of the moisture sensors and other dynamics of the drying cycle in conjunction with the humidity sensor and WRR calculations to improve the consistency and reliability of automatic termination.

2.3.4 Completing the Cycle

Once the WRR algorithm has concluded that the load is dry, the cycle has to be terminated. Drying cycles typically end with a cool down stage, during which the drum continues to rotate and the blower circulates air through the drum with the heaters off. Even though the energy consumed during the cool down stage is minimal and does not significantly impact the EF, cool down was implemented in the WRR algorithm. All the dryers tested have indicators on their display panels that signal when the dryer is in cool down. These indicators where monitored during the preliminary tests to determine the duration of the cool down stage. The length of cool down was generally 4 to 5 minutes, but was not consistent between test loads and dryer settings, and also did not correlate with exhaust temperature. Consequently, cool down was set to a constant 5 minutes in the WRR algorithm, which is the upper bound of the cool down periods measured. Even though the WRR cool down was not entirely consistent with the dryer's normal cool down, the impact on EF and final RMC was minimal.

At the end of the cool down stage, the cycle was terminated and the load was removed from the drum and weighed in order to obtain the final RMC of the load. Instead of the WRR algorithm automatically stopping the dryer, an indicator was activated on the control screen to notify the operator to manually stop the dryer by opening the door. The couple of seconds of delay did not impact EF or final RMC because the heaters were already off and the load was significantly cooled.

3.0 Energy Savings Results

The three sensors were installed and the new WRR algorithm was tested with two commercially-available residential clothes dryers. Test Unit 1 is a standard electric vented dryer, and Test Unit 4 is a standard gas dryer. Testing followed the DOE Test Procedure in Appendix D2 of Subpart B of 10 CFR Part 430 (D2 test), which is the optional procedure for determining energy factor of automatic termination cycles of residential clothes dryers. In addition to the DOE test load prescribed in the Test Procedure, testing was also performed with an 8.45-pound AHAM 1992 load, an 8.45-pound AHAM 2009 load, a 3-pound extreme light load, and 16.9-pound extreme heavy load. The 3-pound AHAM 1992 load was selected as the extreme light load for a standard dryer, and the combination of the 8.45-pound DOE load and the 8.45-pound AHAM 1992 was selected for the extreme heavy load. While not intended to be comprehensive, these loads provided results for loads of varying composition and size.

With the three new humidity sensors installed in the exhaust duct, the first step was to run standard D2 tests using with the new WRR algorithm turned off, in order to confirm dryer performance was unaffected by installation of the new sensors. These tests also facilitated the implementation of the new algorithm by collecting data from the humidity sensors that were used for setting the WRR threshold in the new algorithm, as described in Section 2.3.3. Once the value of the WRR threshold was set, a series of tests were performed, and the results were used to calculate final RMC and EF, which was used to determine energy savings by comparing to the EF of the preliminary tests.

3.1 Test Unit 1 – Front-Load Vented Standard Electric Dryer

Test Unit 1 was tested with the COTTONS automatic termination cycle and with dryness set to NORMAL. Tests were performed with the temperature set on HIGH and on MEDIUM.

3.1.1 Results From the Existing Dryer Termination Algorithm

Table 3.1 shows the results from the preliminary testing of Test Unit 1 with the humidity sensors turned on and the WRR algorithm turned off. Results were obtained for each of five test loads using the COTTONS automatic cycle, the HIGH temperature setting, and the NORMAL dryness setting, while following the D2 test procedure.

The test data from Volume 1 are also included in Table 3.1 for comparison. The results indicate that the dryer is unaffected by the installation of the humidity sensors, as confirmed by the new data being within two standard deviations of the average of the three tests reported in Volume 1.

Table 3.1. Results for drying time, final RMC, and EF for Test Unit 1 from the COTTONS automatic cycle on HIGH temperature and NORMAL dryness settings.

	SENSORS INSTALLED			NO SENSORS INSTALLED FROM VOLUME 1					
Test Load	Drying time (min.)	Final RMC (%)	EF (lbs/kWh)	Drying time (min.)		Final RMC (%)		EF (lbs/kWh)	
				Avg	Std Dev	Avg	Std Dev	Avg	Std Dev
DOE	40.4	0.68	3.17	39.7	0.4	0.58	0.09	3.22	0.05
2009 AHAM	40.6	0.55	3.02	40.2	1.3	0.74	0.05	3.03	0.08
1992 AHAM	37.0	1.41	3.26	36.6	2.0	1.53	0.87	3.27	0.13
Heavy Load	57.1	2.01	3.93						
Light Load	24.8	0.67	2.05						

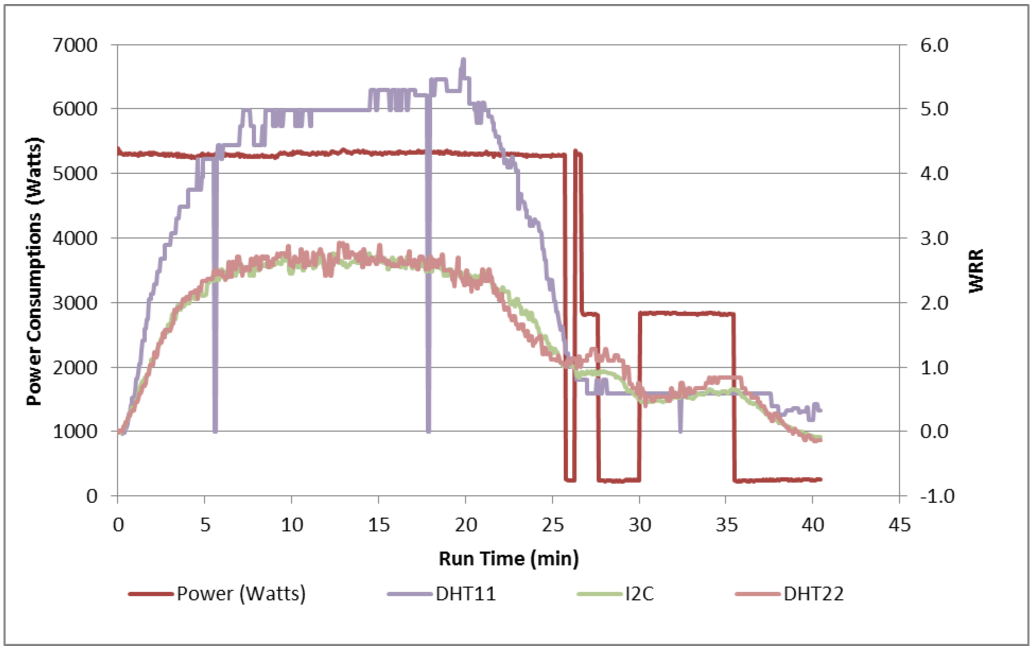


Figure 3.1. WRR traces from Test Unit 1 during a COTTONS automatic cycle using HIGH temperature and NORMAL dryness settings and the DOE test load. The power consumption profile indicates when the one or both heating elements were on.

A secondary purpose of the preliminary testing was to obtain WRR data for each of the sensors in order to select a threshold value for the WRR termination algorithm. Figure 3.1 shows WRR profiles calculated from the humidity sensor data obtained from Test Unit 1. The WRR data from the DHT22 and I2C sensors track very closely. However, the DHT11 sensor gives a similar shape, but different magnitude of the WRR parameter. In addition, the DHT11 has much slower response, poorer resolution, and the signal can be lost as indicated by the downward spikes. Consequently, the DHT22 and the I2C sensor are the better candidates for implementing the WRR algorithm.

3.1.2 Results From the New WRR Termination Algorithm

Based on the WRR data from the five tests in Table 3.1, the WRR algorithm was tested with a WRR threshold of 1.0 using the I2C sensor without the shield. The results of eight tests using the five test loads and two temperature settings are compiled in Table 3.2. All of the tests were performed using the COTTONS automatic cycle and the NORMAL dryness setting per the D2 test procedure. Five of the eight tests were terminated by the new WRR algorithm, and the others were terminated by the existing control system of the dryer. Energy savings were calculated for the WRR terminated tests using the average EF of all previous tests that used the same dryer settings, which is shown on the left of Table 3.2. Energy savings ranged from 7.7% to 23.6% when the new WRR algorithm terminated the cycle. All of the loads were dried to approximately the same dryness except the 3-pound light load, which still met the industry dryness standard of 5% final RMC. All of the loads dried to less than 2% RMC except for the extreme light and heavy loads. The DOE load dried to 0.5% RMC, which is well below the 2% required for a successful D2 test.

It is notable that the three cases that were not terminated by the WRR algorithm also showed shorter drying times and higher EF values than tests run when the WRR algorithm was not turned on. This is most likely due to variability between tests. In particular, there have been insufficient numbers of tests with the light and heavy loads to ascertain variability with these loads. The increase in EF with the AHAM 1992 load is well within the variability seen in results from Volume 1. Additional replicate testing is needed to more accurately quantify the energy savings associated with the WRR algorithm for the various loads. Nevertheless, some energy savings were obviously obtained when the WRR algorithm stopped the dryers early. The savings exceeded the standard deviations of EF from the duplicate tests from Volume 1, which were 2% and 3% for the DOE and AHAM 2009 loads, respectively.

Table 3.2. Results for the new WRR termination algorithm for Test Unit 1 from the COTTONS automatic cycle on NORMAL dryness setting; energy savings included for tests when WRR terminated cycle.

	WRR Algorithm On					WRR Algorithm Off		
Test Load	**Drying time (min.)**	**Final RMC (%)**	**EF (lbs/kWh)**	**WRR Term?**	**Energy Savings (%)**	**Drying time (min.)**	**Final RMC (%)**	**EF (lbs/kWh)**
HIGH Temperature Setting								
Light Load	20.6	4.06	2.68	Yes	23.6	24.8	0.67	2.05
DOE	31.5	0.50	3.64	Yes	12.1	39.9	0.60	3.20
2009 AHAM	34.0	0.79	3.35	Yes	9.5	40.3	0.69	3.03
1992 AHAM	34.8	1.44	3.34	No		36.7	1.50	3.27
Heavy Load	52.9	2.80	4.23	No		57.1	2.01	3.93
Medium Temperature Setting								
DOE	31.2	0.55	3.69	Yes	7.7	37.6	0.50	3.41
2009 AHAM	34.4	1.21	3.47	Yes	8.5	38.9	0.92	3.18
1992 AHAM	34.0	1.99	3.49	No		36.0	2.38	3.36

Results are also presented in bar charts in Figure 3.2 to Figure 3.5. Figure 3.2 also includes the 2015 energy conservation standard for the DOE test load, which represents the standard that a residential dryer must meet with the D2 test[1]. Test Unit 1 came close to meeting the standard with the new WRR algorithm, although standby and off mode energy use will result in a CEF lower than the EF value. Because the final RMC of the DOE load was still significantly below the maximum allowed 2%, additional tuning of the WRR threshold, and/or an improved algorithm, may produce more energy savings.

The trend suggested by the results is that the opportunity for energy savings with the WRR algorithm is primarily with the smaller and more uniform loads. Given that the final RMC of most of the loads is significantly below the 5% final RMC target, additional energy savings may be obtainable with additional effort in tuning the algorithm or further development of an improved algorithm.

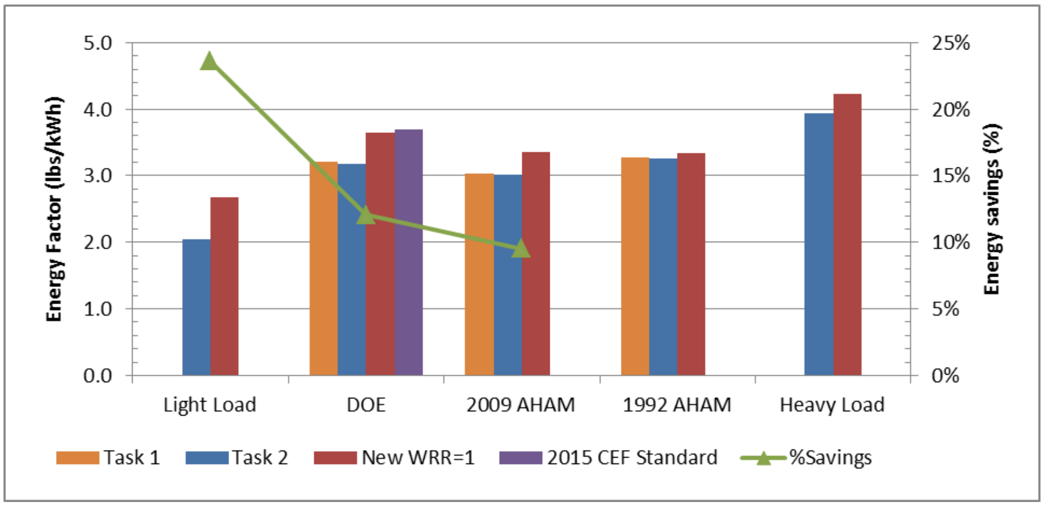


Figure 3.2. Comparison of EFs for Test Unit 1 using the COTTONS automatic cycle and HIGH temperature and NORMAL dryness settings, including energy savings from the new WRR termination algorithm.

[1] Note, the energy conservation standard is for the combined CEF, which includes standby and off mode energy use and is not directly comparable to the EF reported here.

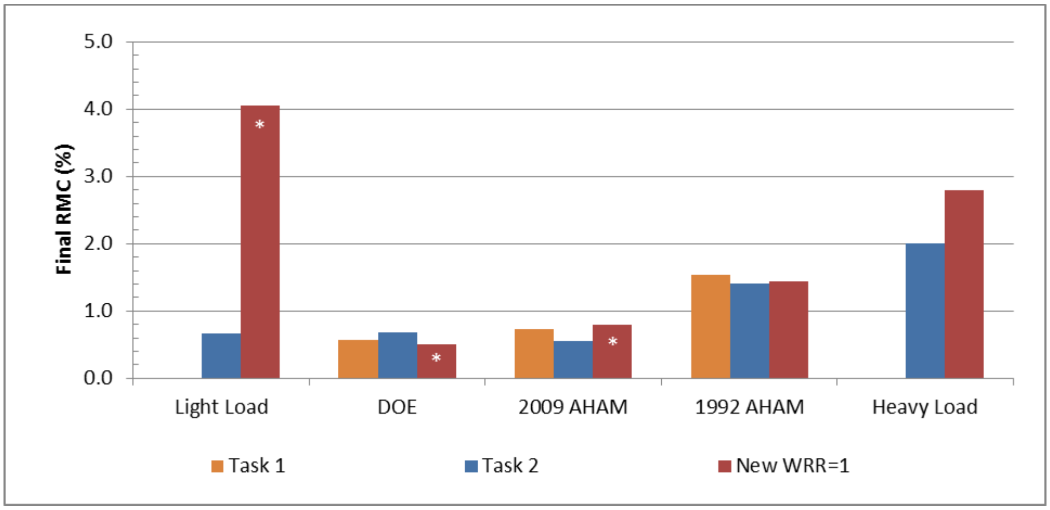


Figure 3.3. Comparison of final RMC values for Test Unit 1 using the COTTONS automatic cycle and HIGH temperature and NORMAL dryness settings (* indicates cycle terminated by the WRR algorithm).

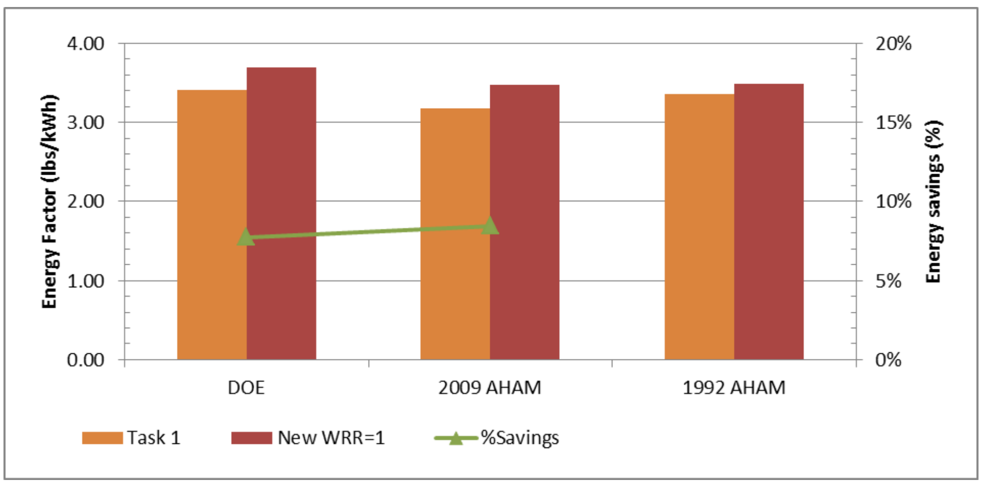


Figure 3.4. Comparison of EFs for Test Unit 1 from the COTTONS automatic cycle using MEDIUM temperature and NORMAL dryness settings, including energy savings from the new WRR termination algorithm.

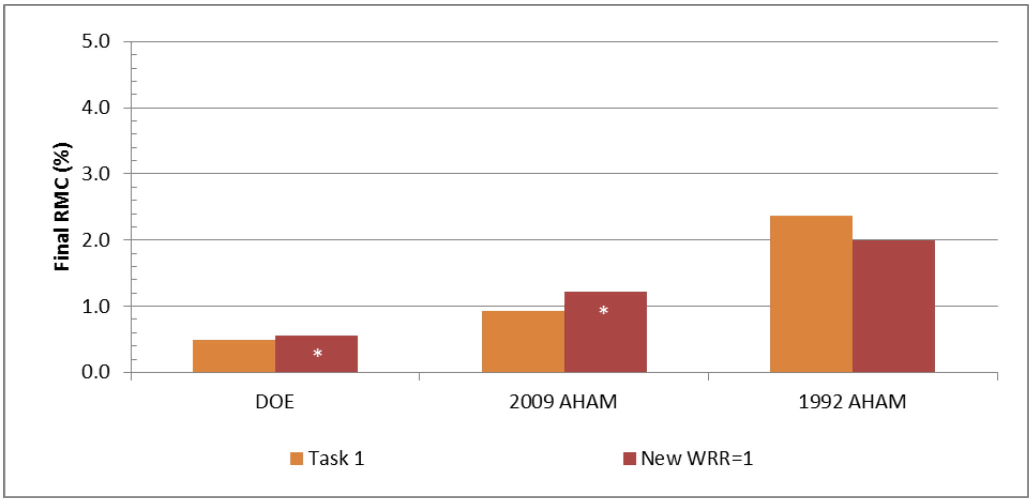


Figure 3.5. Comparison of final RMC values for Test Unit 1 using the COTTONS automatic cycle and MEDIUM temperature and NORMAL dryness settings (* indicates cycle terminated by the WRR algorithm).

3.2 Test Unit 4 – Front-Load Standard Gas Dryer

Following the D2 Test Procedure instructions, Test Unit 4 was tested with the COTTON/NORMAL automatic termination cycle and with dryness set to NORMAL. The temperature setting could not be adjusted independently of the cycle setting, so the temperature setting was MEDIUM. In addition to the D2 procedure, Test Unit 4 was also tested with a HIGH temperature setting using the HEAVY DUTY automatic cycle.

3.2.1 Results From the Existing Dryer Termination Algorithm

Table 3.3 shows the results from the preliminary testing of Test Unit 4 with the humidity sensors turned on and the WRR algorithm turned off. Results were obtained for each of five test loads using the COTTON/NORMAL automatic cycle with the required MEDIUM temperature setting and the NORMAL dryness setting, while following the D2 test procedure.

The test data from Volume 1 are also included in Table 3.1 for comparison. Replicate testing was not performed with Test Unit 4, so standard deviations are not available to conclude whether Test Unit 4 is unaffected by the installation of the humidity sensors. However, the maximum difference in the final RMC and EF is less than 6% between these results and the results from Volume 1. Therefore, it is reasonable to conclude the dryer operation and performance is unaffected by the installation of the humidity sensors.

Table 3.3. Results for drying time, final RMC, and EF for Test Unit 4 from the COTTON/NORMAL automatic cycle on NORMAL dryness setting.

	SENSORS INSTALLED			NO SENSORS INSTALLED FROM VOLUME 1		
Test Load	Drying time (min.)	RMC (%)	EF (lbs/kWh)	Drying time (min.)	RMC (%)	EF (lbs/kWh)
2009 AHAM	37.7	1.37	2.65	36.3	1.31	2.64
1992 AHAM	34.8	2.63	2.82	33.0	2.79	2.86
DOE	36.6	0.79	2.85	35.5	0.78	2.79
Heavy Load	51.2	4.93	3.48			
Light Load	32.7	3.02	1.60			

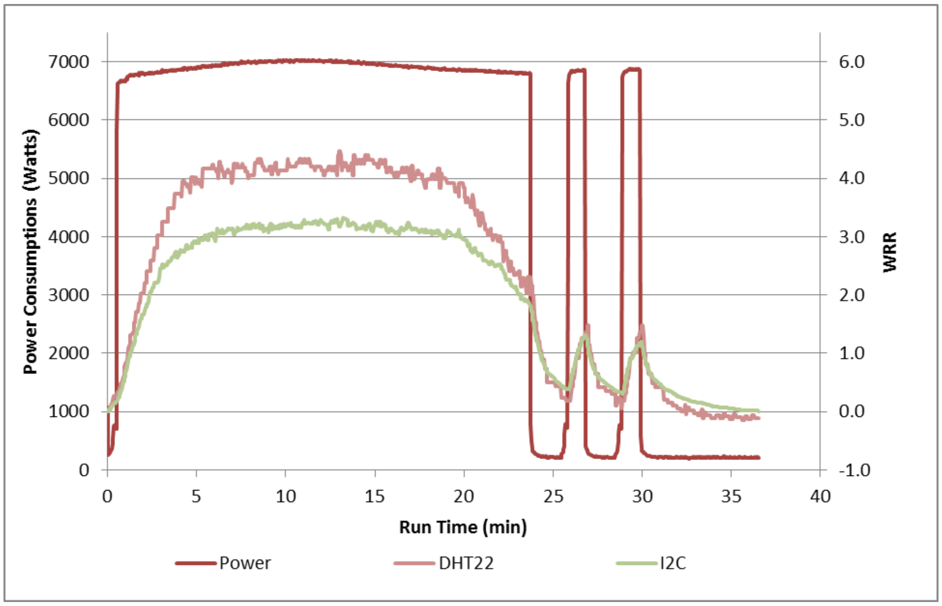


Figure 3.6. WRR traces from Test Unit 4 during a COTTON/NORMAL automatic cycle using NORMAL dryness setting and the DOE test load. The power consumption profile includes the natural gas equivalent higher heating value and indicates when the burner was on.

Figure 3.6 shows WRR profiles calculated from the humidity sensor data. The DHT11 sensor failed, most likely due to prolonged exposure to temperatures outside of its measurement range, and was not used with Test Unit 4. The I2C sensor used in Test Unit 1 tests was damaged while transferring it to Test Unit 4 and was replaced with an I2C sensor that had the shield to protect it from damage during handling and operation. As can be seen in Figure 3.6, the new I2C sensor did not track with the DHT22 sensor as closely. However, because the WRR algorithm uses a threshold value that is adjustable and does not depend on the absolute value of the WRR parameter, the accuracy of the WRR parameter is not critical for the algorithm to be successful.

A more significant issue with the WRR traces in Figure 3.6 is the sharp drop in WRR when the burner turns off. This is caused by the water produced from natural gas combustion, which augments the WRR value when the burner is on. This causes problems with the simple threshold trigger logic for terminating the cycle that was used with Test Unit 1. The algorithm was modified to trigger only at the moment the burner is turned off, as discussed above.

3.2.2 Results From the New WRR Termination Algorithm

Based on the WRR data from the five tests in Table 3.3, the WRR algorithm was tested with a WRR threshold of 2.0 using the DHT22 sensor. While the I2C sensor was successfully used with Test Unit 1, the DHT22 sensor appears to be less susceptible to damage from handling. The algorithm was activated when the WRR parameter reached 3.0 and went into cool down if the WRR was less than 2.0 when the burner turned off. The results of eight tests using the five test loads and two temperature settings are compiled in Table 3.4. The COTTON/NORMAL automatic cycles were performed per the D2 test procedure. The other three tests were performed with the HEAVY DUTY cycle in order to determine potential energy savings from a high temperature cycle.

Four of the eight tests were terminated by the new WRR algorithm, and the others were terminated by the control system of Test Unit 4. Energy savings were calculated for the WRR terminated tests using the average EF of all previous tests that used the same dryer settings, which is shown on the left of Table 3.4. Energy savings ranged from 5.2% to 8.0%. As with Test Unit 1, additional replicate testing is needed to accurately quantify the potential savings with the WRR algorithm. Other than the light and heavy load, all of the loads dried to less than 2% RMC except for the medium temperature test with the AHAM 1992 load, which was slightly higher. The DOE load dried to 0.63% RMC, which is well below the 2% required for a successful D2 test.

Results are also presented in bar charts in Figure 3.7 to Figure 3.10. Figure 3.7 includes the 2015 energy conservation standard for the DOE test load. The standard is for CEF that includes standby and off mode energy use, which must be met by residential gas dryers in 2015. The EF for Test Unit 4 came closer to reaching the CEF standard with the new WRR algorithm, but still tested significantly below the standard.

However, the revised WRR algorithm only determines whether to terminate the load when the burner turns off, and the number of opportunities are limited. Because the final RMC of the DOE load was still significantly below the maximum allowed 2%, an enhanced algorithm may improve the EF further.

Table 3.4. Results for the new WRR termination algorithm for Test Unit 4 on NORMAL dryness setting; energy savings included for tests when WRR terminated cycle.

	WRR Algorithm On					Average WRR Off		
Test Load	**Drying time (min.)**	**Final RMC (%)**	**EF (lb/kWh)**	**WRR Term?**	**Energy Savings (%)**	**Drying time (min.)**	**Final RMC (%)**	**EF (lb/kWh)**
COTTON/NORMAL cycle on MEDIUM Temperature Setting								
Light Load	32.2	2.42	1.60	No		32.7	3.02	1.60
DOE	31.0	0.63	3.03	Yes	6.7	36.0	0.78	2.82
2009 AHAM	32.1	2.10	2.85	Yes	7.2	37.0	1.34	2.64
1992 AHAM	35.7	1.93	2.71	No		33.9	2.71	2.84
Heavy Load	53.7	3.52	3.34	No		51.2	4.93	3.48
HEAVY DUTY cycle on HIGH Temperature Setting								
DOE	33.0	0.39	2.76	Yes	8.0	38.8	0.58	2.54
2009 AHAM	34.3	1.00	2.62	Yes	5.2	37.7	0.73	2.49
1992 AHAM	37.3	1.64	2.58	No		41.3	0.81	2.38

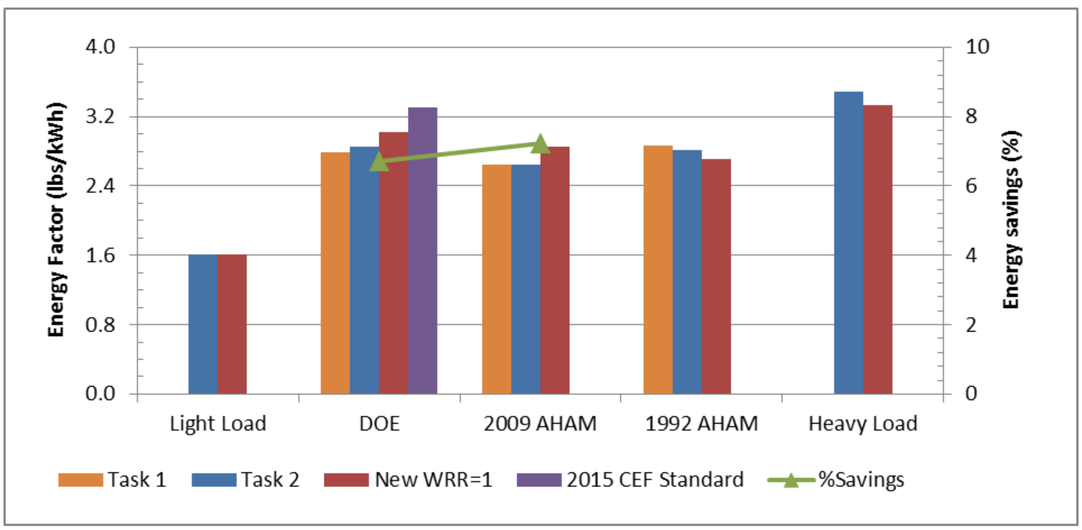


Figure 3.7. Comparison of EFs for Test Unit 4 using the COTTON/NORMAL automatic cycle and NORMAL dryness setting, including energy savings from the new WRR termination algorithm.

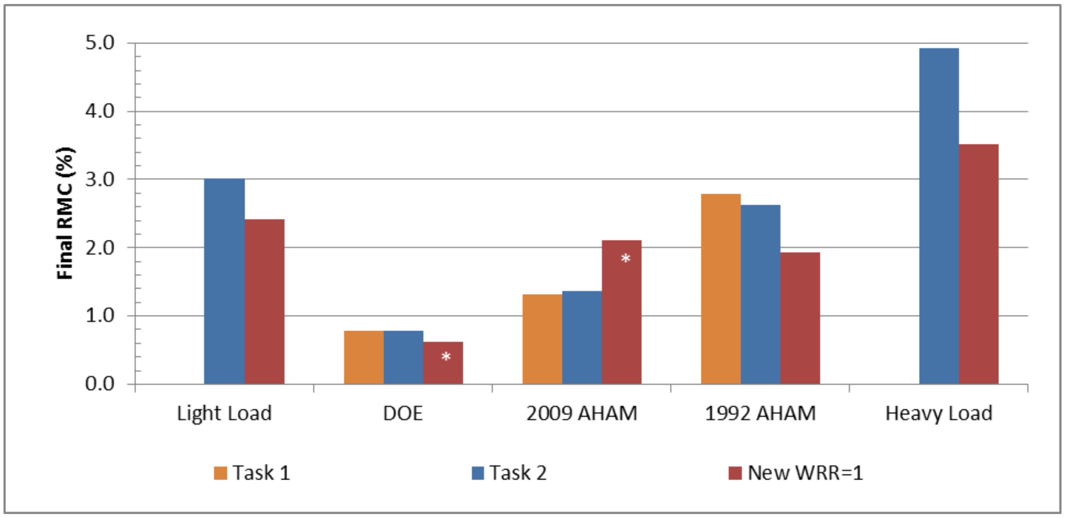


Figure 3.8. Comparison of final RMC values for Test Unit 4 using the COTTON/NORMAL automatic and NORMAL dryness setting (* indicates cycle terminated by the WRR algorithm).

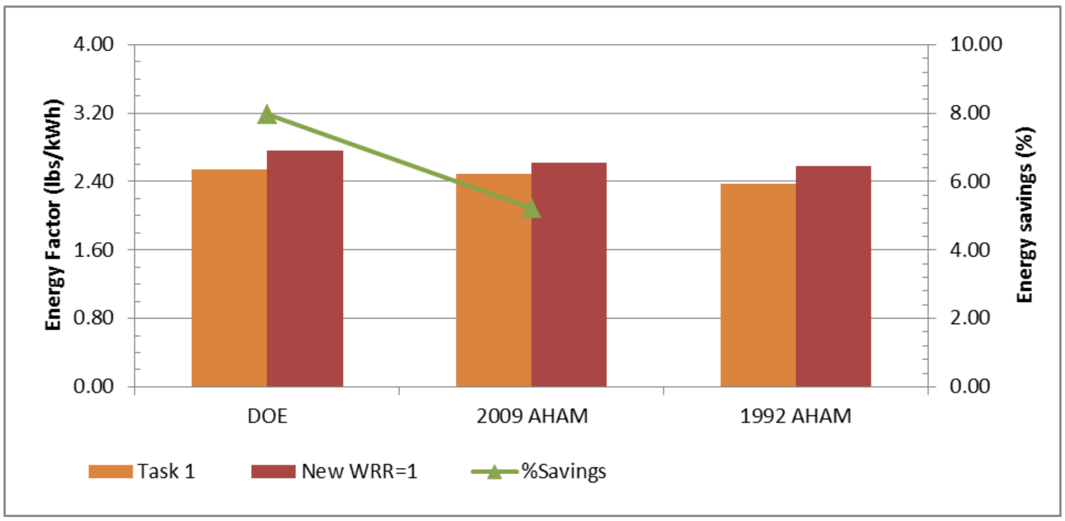


Figure 3.9. Comparison of EFs for Test Unit 4 using the HEAVY DUTY automatic and NORMAL dryness setting, including energy savings from the new WRR termination algorithm.

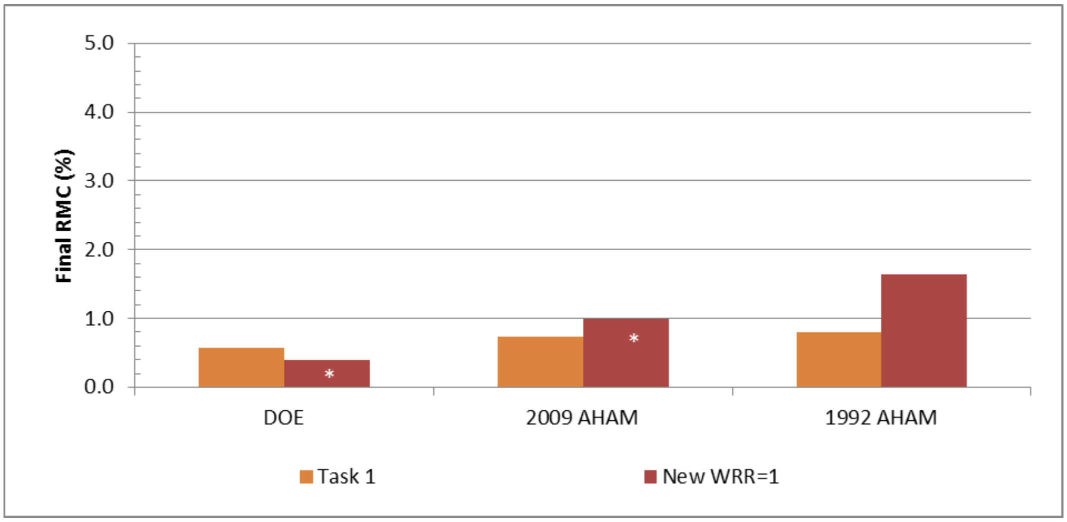


Figure 3.10. Comparison of final RMC values for Test Unit 4 using the HEAVY DUTY automatic and NORMAL dryness setting (* indicates cycle terminated by the WRR algorithm).

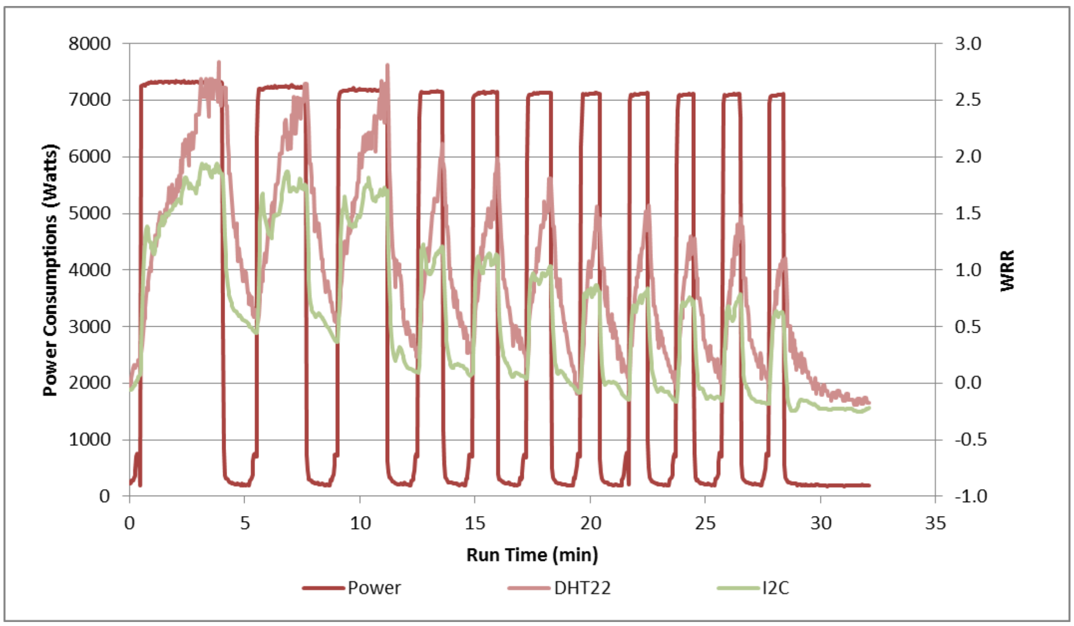


Figure 3.11. WRR traces from extreme light load with Test Unit 4 using the COTTON/NORMAL automatic cycle and NORMAL dryness setting. The power consumption profile includes the natural gas equivalent higher heating value and indicates when the burner was on.

The Test Unit 4 results are consistent with the trend found with Test Unit 1 showing the WRR algorithm is more effective with smaller and more uniform loads. The exception was the extreme light load that was only 3 pounds. In this test, the WRR algorithm never activated; the reason is understood from the WRR traces shown Figure 3.11. With the extreme light load, there is insufficient water in the load to use all of the natural gas heat for evaporation, so the dryer begins cycling the burner on and off early—at about 4 minutes in Figure 3.11—in the drying cycle to prevent overheating. This prevents the WRR from ever reaching the trigger value of 3.0, so the algorithm never activates. The trigger could be lowered so that the cycle would activate. However, with a WRR threshold of 1.0, the algorithm would terminate after the 6th time the burner turns off, but the load would still be too wet. The conclusion is that a more complex algorithm is needed to save energy with the extreme light loads, which is beyond the scope of this effort.

4.0 References

[1] 78(1) FR 152-185. January 2, 2013. "Energy Conservation Program: Test Procedures for Residential Clothes Dryers" U.S. Department of Energy, Federal Register.

[2] 78(157) FR 49608-49651. August 14, 2013. "Energy Conservation Program: Test Procedures for Residential Clothes Dryers" U.S. Department of Energy, Federal Register.

[3] 10 CFR 430 subpart B Appendix D. 2014. "Uniform Test Method for Measuring the Energy Consumption of Clothes Dryers" U.S. Environmental Protection Agency, Code of Federal Regulations.

[4] AHAM HLD-1-2009. 2009. "Household Tumble Type Clothes Dryers." Association of Home Appliance Manufacturers, Washington, DC.

[5] AHAM HLD-1-1992. 1992. "Household Tumble Type Clothes Dryers." Association of Home Appliance Manufacturers, Washington, DC.

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