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NATURAL GAS PROGRAM

FINAL REPORT

Energy-Efficiency Clothes Dryers: Self-Calibrating Automatic Cycle Termination Controller

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Acknowledgement Page

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Abstract

This project developed an automatic dryer cycle termination controller that utilized the relationship between dryer drum inlet temperatures and outlet temperatures to accurately predict the end of the drying cycle. The technology promises to be more accurate and robust in performance under different load and environmental conditions in comparison to existing technology. The low-cost automatic controller was demonstrated in the laboratory to reduce energy use in gas clothes dryers by accurately terminating the drying cycle when the remaining moisture content of the load is 2% or less. In a standard DOE test conducted three times, the controller shut-off the dryer when 2% remaining content was predicted and measured results showed a remaining moisture content of 1.62%, 1.89%, and 1.93% for the three tests. For drying the DOE standard test load, the controller used between 5-15% less total energy in comparison to three gas dryers tested by DOE. The accuracy of the controller was also demonstrated for other load types under other environmental conditions. An additional outcome of the project was determination of a method to use the information obtained in the drying cycle to predict real-time energy efficiency metrics that can be used to track dryer performance with time as a means for fault detection and to provide information to the consumer.

Key Words: clothes dryer controls, clothes dryer energy efficiency, automatic cycle termination, automatic shut-off, real-time energy efficiency metrics

Executive Summary

Introduction

In the interests of promoting energy efficiency and satisfying consumers, there has been a move toward automatic termination controllers in residential dryers, which use some method of sensing to determine when the load is dry. However, available test data shows that these control systems do not fare well when their energy efficiency performance is measured. To gather data on the effectiveness of the automatic termination controls for dryers, the Department of Energy (DOE) tested a number of electric and gas dryers at an independent test laboratory (Table 1) [1]. For the eight dryer models tested, the automatic termination feature used 4-62% more energy than was required to dry the clothes to the remaining moisture content (RMC) standard of 2%. This means that in all cases tested, the dryer ran the heat substantially longer than required to meet the standard. Furthermore, it should be noted that these tests were completed under DOE standard test conditions with new equipment, a specified test load, and where the inlet room air temperature was modulated to be 75±3°F. Performance may vary under different environmental conditions, load types, and as sensor accuracy drifts with time.

Project Objectives

The goal of this project was to determine the feasibility of a low-cost self-calibrating automatic controller that will reduce energy use in gas clothes dryers by 20% or more by accurately terminating the drying cycle when the remaining moisture content of the load is 2% or less.

The project performance and cost objectives to achieve this overall goal were:

1. Confirm hardware measures differential temperature signal with an accuracy of 0.5°F.
2. Confirm test stand is capable of testing dyer to specifications of DOE Appendix D2.
3. Demonstrate control shuts off gas heat within two minutes when remaining moisture content is 2% or less.
4. Demonstrate energy consumption using auto shut-off as measured by DOE Appendix D2 is of 2.6kWh or less.
5. Confirm sensors and controller can be manufactured at a cost not to exceed $25 to the dryer manufacturer.

Project Outcomes

The researchers designed and tested several control schemes, building and learning from the experimental results as the project progressed. The final control scheme design monitored the rate of change of the temperature difference between the inlet and outlet dryer temperatures. With this design, the researchers determined the actual accuracy of the measured temperature values were not critical. Therefore, demonstration of the 0.5°F signal accuracy was not a requirement for the controller based on the final design and was not further pursued.

The researchers constructed a test stand at the University of California, Davis, which largely satisfied the requirements of DOE Appendix D2. A few of the requirements were not satisfied because they were cost prohibitive and were not expected to significantly impact the test results. Researchers used utility provided natural gas instead of laboratory grade natural gas, and accounted for this by using the highest heating value of the fuel reported by the utility providing the gas service (which was 1.7% higher than the heating value specified by the test standard). Also, it was not possible to condition the tests cloths with the specific water temperature and hardness, however, this is not expected to impact the results.

For the final controller design, three repeats of the DOE Appendix D2 test were conducted. For the DOE test load, a load with 2% remaining moisture content would weigh 8.6 lb. For three repeats of the DOE Appendix D2 test, the final weight of the dry load when the controller shut-off the dryer was 8.568 lb, 8.591 lb, and 8.595 lb, which equates to a remaining moisture content of 1.62%, 1.89%, and 1.93% respectively. The measured evaporation rate near the end of the cycle was 0.005 lbw/second, meaning that the controller shut off the dryer within 7 seconds of reaching a remaining moisture content of 2%. The total energy consumption (converted to kWh) for each load was: 2.80, 2.69 and 2.61 kWh (average: 2.70 kWh). This is 4% higher than the target objective of the project: 2.6 kWh.

The estimated cost for the controller when the components are purchasing in large volume (10,000 units) was estimated at $24, which is less than the $25 target cost. Additionally, the output relays and power supply may be redundant with components used in existing dryer controllers, so that the incremental cost over existing controllers may be substantially less.

Conclusions

An automatic dryer cycle termination controller was developed and proof-of-concept was demonstrated. The performance objectives of shutting off the dryer when obtaining 2% remaining moisture content was met, however, the average energy consumption was 4% higher than the target of 2.6 kWh for the DOE standard test load. In addition to the DOE Appendix D2 tests, the researchers tested the controller with a variety of different load types with different room air conditions. The controller automatically shut off the dryer when the load was determined to be dry, and the measured remaining moisture content at the end of the test varied between 1.62 - 6.68%. All but one test had a remaining moisture content between 1.62 - 5%, where 5% is higher than the DOE test standard of 2%, however, would still be considered by consumers as “dry”. The energy consumed for the drying cycles varied between 1.4-4.13 kWh, where the energy consumption was a function of the size and composition of the load.

In summary, the controller provides the following advantages over existing dryer controllers:

1. The temperature difference sensing technology is not impacted by specific inlet air conditions.
2. Sensors can be configured so that actual contact is not necessary between dryer contents and the sensor(s).
3. The sensor and controller can estimate average moisture content (dryness) of the contents of the dryer instead of relying on sensing only items that intermittently come into contact with the sensor.

4. The data used to determine when to terminate the drying cycle can also be used to provide energy efficiency reporting metrics.

Recommendations

The technology developed from this project shows significant promise and, as a result, the researchers have filed for intellectual property protection. The University intends to pursue licensing of the technology to a dryer manufacturer, which is the most practical path forward for the technology. The researchers have made initial steps to secure additional funding from a California utility to test the concept in electric dryers, where it is expected that the same principles would apply. Further research to support commercialization could include:

1. Additional data correlating the load size to the temperature response of the dryer when the burner fires
2. Improving signal processing techniques in order to reduce errors in calculating the maximum temperature difference and associated drop of the temperature difference when the load is "nearly dry"
3. Testing the controller in different models and brands of dryers
4. Testing the controller in comparison to other existing controllers under load and room conditions that vary from the DOE Appendix D2 standard
5. Exploring calculation and application of real-time energy efficiency tracking metrics

Public Benefits to California

In this project, the controller demonstrated a cycle efficiency of 2.70 kWh per load using the DOE Appendix D2 test procedure. This is in comparison to test data for three other cycle termination controllers tested by the DOE that had results of 2.91, 3.16, and 2.84 kWh (average 2.97 kWh) [3]. The performance of the controller design in this project in comparison to the three controllers tested by DOE indicates a savings of 5-15%. Even larger savings are expected under test conditions that vary from the DOE Appendix D2 test procedure, and this is an area indicated for future research. Potential energy savings from possible development of energy efficiency reporting metrics for fault detection and/or influencing user behavior are also possible. A 10% savings estimate is a conservative estimate from which the possible benefits to deploying this controller in California can be calculated.

According to the California Energy Commission's 2009 Residential Appliance saturation survey, gas dryers consume 6% of total residential natural gas use [1]. Residential natural gas use consumes 4,854 million therms in California per year [7]. Based on this data, residential gas dryers consume 291 million therms per year. Saving 10% of dryer natural gas use with 10% penetration equates to approximately 3 million therms per year (or $3 million per year to California residents, assuming an end-use natural gas price of $1 per year). This equates to approximately 35,000 tons of carbon dioxide equivalent greenhouse gas emissions per year [8]. Additional savings are expected over time in commercial environments with dryers (such as hotels, laundromats, athletic clubs, etc).

Introduction

According to the California Energy Commission's 2009 Residential Appliance saturation survey, gas dryers consume 6% of total residential natural gas use [1]. There is extensive evidence that clothes dryers consume unnecessary energy by continuing to run well past the point where clothes are dry [2] [3] [4] [5]. Clothes dryers operate with two basic types of controls: timed dry and/or automatic termination. A timed dry shuts of the dryer after a pre-determined period of time set by the user, which is likely to result in under or over-drying the contents. Automatic termination uses sensors and a controller to determine when the clothes are dry and automatically shuts of the dryer.

In the interests of promoting energy efficiency and satisfying consumers, there has been a move toward automatic termination controllers, which use some method of sensing to determine when the load is dry. However, available test data shows that these control systems do not fare well when their energy efficiency performance is measured. To gather data on the effectiveness of the automatic termination controls for dryers, the Department of Energy (DOE) tested a number of electric and gas dryers at an independent test laboratory (Table 1) [3]. For the eight dryer models tested, the automatic termination feature used 4-62% more energy than was required to dry the clothes to the remaining moisture content (RMC) standard of 2%. This means that in all cases tested, the dryer ran the heat substantially longer than required to meet the standard. Furthermore, it should be noted that these tests were completed under DOE standard test conditions with new equipment, a specified test load, and where the inlet room air temperature was modulated to be 75±3°F. Performance may vary under different environmental conditions, load types, and as sensor accuracy drifts with time.

Table 1 – Excess energy consumed by automatic termination of dryer as reported by DOE, where 2% remaining moisture content (RMC) is considered "dry" [3].

Product Class	Sensor Technology	Energy Consumption (expressed as kWh): To Reach 2% RMC	Energy Consumption (expressed as kWh): End of Cycle Automatic Termination	Excess Energy Consumption
Vented Electric Standard	Moisture + Temp	2.07	2.62	26.8%
	Temperature	2.23	3.12	39.7%
	Moisture + Temp	2.32	2.41	3.8%
	Moisture + Temp	2.28	3.14	37.8%
Vented Electric Compact (240V)	Temperature	0.88	1.42	62.1%
Vented Gas	Moisture + Temp	2.57	2.91	13.1%
	Moisture + Temp	2.53	3.16	24.8%
	Moisture + Temp	2.48	2.84	14.5%

While dryer manufacturers do not publicize their control algorithms, the DOE testing categorized dryers as either containing contact moisture or exhaust temperature sensors. A contact moisture sensor is a conductivity sensor that is shorted when moist clothes pass over the sensor. One limitation of this strategy is that the load may dry unevenly, so that the clothes in contact with the sensor may not be representative of the entire load. Additionally, these sensors can malfunction when obstructed by lint or coated in fabric softener, and can be damaged by dryer contents. Another approach uses exhaust temperature measurements to determine dryness. There are two problems with the temperature measurement method: 1) the temperature of the exhaust will vary with inlet air temperature irrespective of content dryness (particularly if the dryer is located in unconditioned space such as the garage), and 2) the calibration of the temperature sensor may drift with time. Research has been conducted that investigates relative humidity sensing in the control algorithm [4], however, low-cost relative humidity sensors have lower accuracy and stability compared to temperature sensors.

Historically, dryer manufacturers have not had significant motivation to develop accurate and reliable cycle termination controllers because dryer minimum efficiency standards do not require testing the automatic termination feature. While this remains the case, on January 1st, 2015, Energy Star implemented a new Clothes Dryer Certification that requires meeting an efficiency requirement for a drying cycle with automatic termination controls. While the Energy Star program should move the competitive market in the right direction, low-cost, reliable automatic termination technologies are needed to achieve Energy Star goals.

Through this project, a novel, yet relatively simple and inexpensive approach was developed and tested to improve automatic termination controls for clothes dryers. The automatic control measures the temperature of the air as it enters the drum (i.e. after heating) and the temperature of the air exiting the drum (Figure 1). When water is being removed from the load, the temperature of the exhaust air is lower than the temperature of the heated inlet air (due to cooling provided by the evaporated water). While the contents are drying, the differential temperature of the exhaust air in comparison to the inlet air will plateau. When the contents are nearly dry, the differential temperature of the exhaust air in comparison to the inlet air will decrease. This project developed control algorithms to detect these signal changes, determine remaining drying time, and shut off the gas heat and enter the cool down cycle. The objective of the proposed research is to shut off the gas heat within two minutes of when the remaining moisture content reaches the DOE specification of 2%.

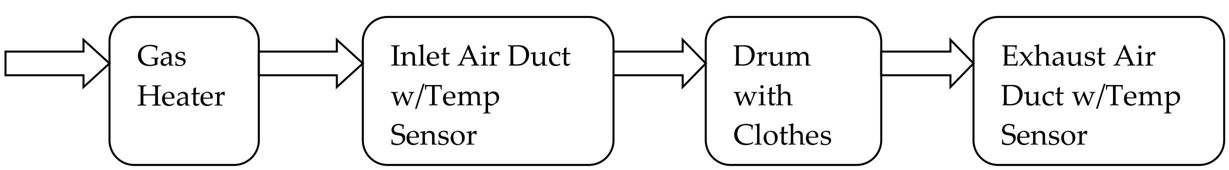

Figure 1 – Location of sensors for automatic clothes drying sensing technology

Because accurate measurement of the temperature differential is critical, the project will develop and test a method to self-calibrate the signal periodically (for example, monthly) when the dryer is not in use. During calibration, the fan and heater will run for a short time and the exhaust sensor temperature value will be compared to the inlet temperature to re-calibrate the temperature differential endpoint. In the described system, the important measurement is the relative signal between the two sensors and not the actual temperature. This strategy resolves several problems with existing control systems:

1. The differential signal is not impacted by the inlet air condition, as is the case for a control system that attempts to determine dryness based on a single exhaust temperature value.
2. The sensors are not subject to contact with dryer contents, as is the case for a moisture sensor that is in contact with (and likely damaged by) dryer contents.
3. The system will periodically self-calibrate to maintain sensor accuracy over the lifetime of the dryer. Existing state-of-the-art sensors do not assure accuracy over time.

Project Objectives

Project Goal: The goal of this project was to determine the feasibility of a low-cost self-calibrating automatic controller that will reduce energy use in gas clothes dryers by 20% or more by accurately terminating the drying cycle when the remaining moisture content of the load is 2% or less.

The project performance and cost objectives that were identified to achieve this overall goal were:

1. Confirm hardware measures differential temperature signal with an accuracy of 0.5°F.
2. Confirm test stand is capable of testing dyer to specifications of DOE D2.
3. Demonstrate control shuts off gas heat within two minutes when remaining moisture content is 2% or less.
4. Demonstrate energy consumption using auto shut-off as measured by DOE Appendix D2 is of 2.6kWh or less.
5. Confirm sensors and controller can be manufactured at a cost not to exceed $25 to the dryer manufacturer.

Project Approach

Task 1: Design sensor and controller hardware and fabricate two prototypes

Several temperature sensing and control prototypes were fabricated and implemented in a Samsung residential gas clothes dryer, model #DV330AGW. More specifically, temperature sensing strategies included two prototypes:

1. *Surface mounted resistive temperature detectors (RTDs)* to measure the temperature of the dryer inlet air duct and the outlet air duct,
2. *Air temperature RTDs* to measure the temperature of the dryer inlet air and outlet air, and

Photos were taken of the installed surface temperature sensors, however the air temperature sensors are inside the ducts were not photographed (Figure 2).

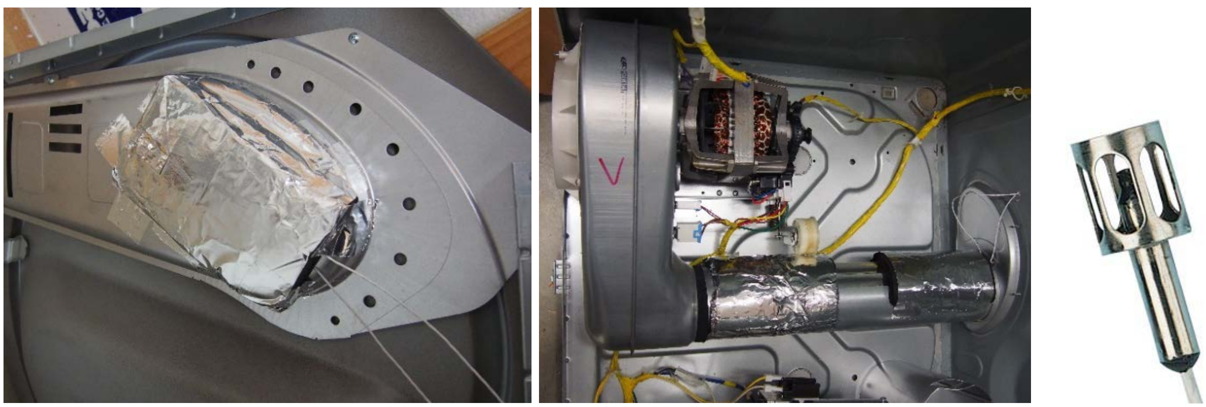

Figure 2 –Surface mounted RTDs installed on dryer air inlet duct (left) and dryer air outlet duct (middle) and example air temperature RTD (right).

The dryers existing controls were bypassed and two additional relays were added to achieve individual on/off control of both fan/drum motor and the gas burner. The control prototypes measured and stored the values of the sensors at a frequency of 1Hz using National Instruments hardware and LabVIEW software. Several versions of the control algorithm were implemented using custom LabVIEW software. The prototype hardware and software also controlled the fan/drum motor and the gas heater as specified by the algorithm under test.

Task 2: Design controller algorithms including auto-calibration and automatic shut-off features

The research team designed, implemented, and tested multiple iterations of the control algorithm over a six month period in order to develop and refine the automatic shut-off feature. All control algorithms investigated relationships between a measurement of the dryer inlet temperature (air or duct surface) and dryer outlet temperature (air or duct surface), which for simplicity is also called the "temperature difference." The approaches tested included determining dryness based on:

1. The temperature difference and its theorized approach to zero, which was the originally proposed strategy.
2. The change of the temperature difference over time, which was further evaluated to study the relationship of this metric to:
    a. The remaining water in the load
    b. The weight of the load

The final design of the automatic shut-off feature negated the need for the automatic-calibration feature, and this was not designed or tested. Further explanation of this provided in the project results section.

Task 3: Fabricate a test stand to specifications of a DOE Appendix D2 by instrumenting a commercially available gas dryer.

The test stand controlled temperature and humidity of the test environment to meet the requirements of DOE test procedures. Construction consisted of a wood frame chamber with foam board insulation with dimensions approximately 8′x8′x8′ (Figure 3). An existing supply fan delivered air to the chamber through two coils. The first coil supplied chilled water from a rooftop chiller at 38°F for chilling and dehumidification. The second coil supplied hot water from a rooftop boiler at 160°F for heating. The chamber temperature control design involved modulating the water flow rates with a control loop feedback mechanism. The DOE standard test condition is a temperature of 75°F ± 3°F and relative humidity 50% ± 10%. The test chamber was designed to meet this test condition as well as other test conditions at temperatures between 65-95°F.

An existing laboratory natural gas supply was extended 50 feet to supply gas to the test chamber. A shut off valve and regulator were installed (Figure 3). The dryer with the prototype sensors was installed in the chamber. A Samsung WF220 washing machine was also installed in the chamber to pre-condition the loads for drying.

The test chamber was instrumented to control the chamber temperature (Figure 4). Instrumentation included monitoring the temperature and relative humidity of the test chamber, temperature and relative humidity of the exhaust air, temperature sensing in multiple dryer locations, natural gas mass flow rate, and electricity consumption and power (Table 1). A high accuracy scale was procured to weigh the clothes to determine the remaining moisture content (Table 1).

In addition to measurements required by the DOE test procedures, the remaining water in the load during the entire drying cycle was tracked through calculation of the absolute humidity of the air entering and exiting the dryer. The capability was added to add real-time information about the drying process which was used to develop the control algorithm. This capability is not needed for testing the final performance of the algorithm. At the start of the test, the researchers measured the initial water in the load (in lbs) and input this number into the test software. Then, at every time step, the data acquisition system:

1. Calculated the absolute humidity of the air exiting the dryer in lb of water per lb of air (lbw/lba) from measurements made by the Vaisala HMD70Y exhaust air sensor.
2. Subtracted the absolute humidity of the air entering the dryer in lbw/lba, which was calculated from measurements made by the Vaisala HMD70Y room air sensor. This is change in humidity of the air through the dryer.
3. Multiplied the change in absolute humidity by the measured airflow rate and time step to obtain lbs of water removed from the dryer.
    a. Airflow rates were measured using a high accuracy CO_2 tracer gas measurement system, a tool previously developed by the Western Cooling Efficiency Center. In this process, carbon dioxide is injected into the airstream at a known rate and the resulting concentration of carbon dioxide is measured downstream of the injection in the mixed airstream.
4. Subtracted the water was added to the system because of the combustion of natural gas. The amount of natural gas combusted was calculated from the mass flow rate of natural gas measured by the Alicat MW-500SCCM-D/5M sensor multiplied by the time step. Natural gas combustion was converted to water added by estimating that one lb of natural gas combustion produces 2.25 lb of water.
5. Calculated the amount of remaining water in the load, based on the initial water and the water removed up to the current time.

Figure 3 – Insulated wood frame chamber with heating, cooling, and dehumidification capabilities (left) and gas line and regulator (right).

Figure 4 –Diagram of the instrumentation of the test chamber and dryer.

Table 2 – Instrumentation for the test chamber and dryer.

Diagram Label	Measurement	Qty	Model Number	Accuracy	Doe Test Standard Required Accuracy [3]	DAQ
T_{in}	Surface Mounted Inlet Temp	2	Omega SA1- RTD	+/- 0.6 °F	Not applicable	NI 9217
T_{out}	Surface Mounted Outlet Temp	2	Omega SA1- RTD	+/- 0.6 °F	Not applicable	NI 9217
$T_{out,air}$	Outlet Air Temperature	1	Omega RTD-806	+/- 0.6 °F	Not applicable	NI 9217
T_{cab}	Dryer Cabinet Temperature	3	Omega HSRTD-3-100-A-120-E	+/- 0.6 °F	Not applicable	NI 9217
V_{gas}	Mass Flow Rate of Natural Gas	1	Alicat MW-500SCCM-D/5M	0.4% of reading + 0.2% of full scale	0.5% of reading	Serial
E	Power, Electricity	1	Powerscout 3 Plus	Accuracy +/- 0.5 % Resolution 0.01 Wh	Accuracy +/- 0.5 % Resolution 1 Wh	Serial
$T_{room,}$ RH	Room Temp, RH	1	Vaisala HMD70Y	+/- 2% RH +/- 0.4°F	+/- 2% RH +/- 1.0°F	NI SCB-68
$T_{exhaust,}$ RH	Exhaust Temp, RH	1	Vaisala HMD70Y	+/- 2% RH +/- 0.4°F	+/- 2% RH +/- 1.0°F	NI SCB-68
N/A	Weight of clothes	1	GBK 16a	Accuracy 0.006 lb Resolution 0.0032 oz	Accuracy 0.009 lb Resolution 0.2 oz	Handheld display

Task 4: Finalize Test Plan

a. Obtain EISG Approval of Test Plan

The test plan was written and submitted to EISG on September 8, 2015 and approved on September 10, 2015. The test plan described the experimental setup presented in Task 3, as well as plans to develop and test the control algorithm. The test plan proposed to:

1. Measure and analyze the time response of the inlet and outlet temperatures of the prototype sensor installations
2. Evaluate the temperature response of the dryer with no load.
3. Evaluate the temperature response of the dryer with a dry load.
4. Evaluate the temperature response of the dryer with a normal (wet) load.
5. Measure the effectiveness of the implemented control scheme, including the impacts on natural gas and electricity consumption.

Task 5: Conduct Prototype Testing for Two Design Alternatives

a. Resistive temperature design (RTD)
b. Thermocouple/thermopile design

As described in Task 1, two different sensor design options were evaluated, which were all designs using RTD sensors. No thermocouple/thermopile designs were tested. The best RTD design was selected from Task 1, the best control algorithm design was implemented from Task 2, and final testing was completed.

The final algorithm was tested with a variety of content types including DOE standard test cloths (1), two heavy sweatshirts (2), jackets (3,4), combination of sweatshirts, jackets and fleece (2,3,4,5), cotton towels (6), a mixed load of kids clothes and sheets (not pictured), and mixed cloth rags with varying load sizes (7, 8, 9) (Figure 5). The tests with DOE standard test cloths tests were completed at DOE standard room test conditions (75°F, 50% RH). The remaining tests were run at a variety of conditions to sample the types of conditions an actual consumer may use their dryer in. For each test, the following data was collected to determine the performance of the controller: room temperature, room humidity, bone dry test weight, initial test weight, post-test weight, drying cycle length, natural gas consumption, electricity consumption.

Figure 5 - Example Loads

Task 6: Perform Manufacturing Cost Analysis

The hardware requirements were dictated by the final design of the control algorithm and the original project objective for the controller to cost $25 or less. After designing the controller, the research team used an online electronic component website, digikey.com, to select the various components needed to meet the minimum requirements for the algorithm. To provide more realistic pricing for a scenario where a large number of units is manufactured, a bulk-pricing level of 10,000 units was used to determine the final cost for each component.

Project Outcomes

An overview of the control algorithm process and outcomes are described, followed by a review of outcomes as they relate to the initial project objectives.

Designing Control Algorithms and Initial Prototypes

Designing the control algorithm involved five phases described in the following sections: determining sensor placement and type, evaluating inlet versus outlet temperature trends, correlating the control signals to real-time dryness, correlating the temperature differential to the remaining moisture, and correlating temperature response to load size.

Sensor Placement and Type

The first step of the algorithm development was to select temperature sensors to measure inlet and exhaust temperatures. An analysis comparing surface temperature RTDs versus air temperature RTDs showed that the inlet air temperature sensor signal was greatly affected by proximity to the flame, likely due to radiation (Figure 6, left). In addition, it was difficult to mount the sensor in the air stream because of the high temperatures. The surface temperature measurement proved more practical and less noisy. On the outlet side, the air temperature and surface temperatures were very similar (Figure 6, right). Meeting the performance objective requires a stable temperature difference signal between the inlet and the outlet temperatures; the actual temperature reading is not important. With this objective in mind, the measurements from the surface mounted temperature sensors (1) were selected. Although the original research plan included testing a thermocouple type sensor, it became clear that resistive temperature sensors are much more common in appliances and would work well in this application. Therefore, the research did not evaluate thermocouples.

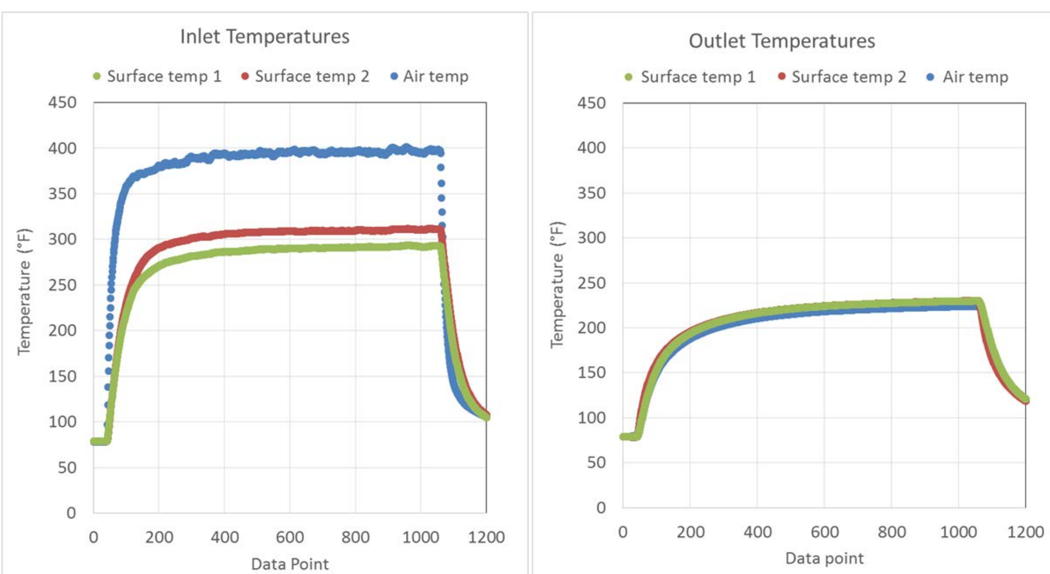

Figure 6 - Inlet and outlet air temperatures for the gas dryer with an empty drum, where each data point represents a 1.5 second data recording interval.

Initial Comparison of Inlet to Outlet Temperature

An example drying cycle was used to compare the dryer inlet temperature to outlet temperature and to evaluate whether controlling the dryer to shut off at a temperature difference near zero would work (Figure 7). The inlet temperature of the dryer rises quickly within 5 minutes when the burner turns on. The outlet temperature of the dryer rises more slowly than the temperature of the inlet air and the steady state temperature of the outlet air is significantly reduced in comparison to the inlet temperature. The researchers determined three contributing factors for this:

1. Evaporating water, which reduces the dryer outlet temperature, as expected.
2. Heat losses from the drum to the environment (dryer cabinet, room)
3. Infiltration into the dryer drum from the room air, meaning that the outlet air is a combination of the heated inlet air and the room air.

In order to quantify the amount of infiltration air, a high accuracy CO_2 tracer gas measurement system was used to measure the inlet and outlet air flow rates. The infiltration air was calculated from the difference of the two. The inlet air flow was 75 CFM, the outlet flow was 135 CFM, and infiltration flow was 60 CFM. This means that the infiltration airflow is affecting the outlet airflow temperature almost as much as the inlet airflow. The researchers also measured the effect of the mass of the contents in the dryer on the rate of airflow. The impact was found to be minimal and on the order of 10%. For contents ranging from 5 pounds to 9 pounds the outlet airflow was 125 ± 10 SCFM.

The original concept of the project was to evaluate the state of dryness of the contents based on the temperature difference, however, the compounding factors of the heat loss from the drum and the infiltration into the dryer significantly complicated this control strategy, because the signal from the evaporating water is small in comparison to the heat losses from the drum and from room air infiltration. Furthermore, it is likely that this type of control would be unreliable in changing environmental conditions that would affect the heat loss rate from the drum and the temperature of the infiltration air.

The researchers shifted focus correlating the rate of change of the temperature difference (inlet-outlet) over time to the dryness of the load (Figure 7, gray line). This strategy does not require the temperature difference to reach any specific value but rather evaluates the changing shape of the curve. For example, in Figure 7, the temperature difference (inlet-outlet) reaches a maximum value of approximately 180°F and then begins to drop slightly as the load dries. The researchers theorized that setting a threshold on a reduction from the maximum difference would correlate to a reliable metric indicating dryness of the load.

In switching to a control scheme where there are no absolute set points, but only relative set points, the accuracy of the sensor readings becomes much less important. In the proposed control scheme, a drop from the maximum difference would indicate dryness, therefore the actual value of the maximum difference number is irrelevant. For example, if the inlet dryer temperature sensor is reading artificially high because of an incorrect calibration, the difference between the inlet and outlet will also be high, however, the drop will still be detected as the clothes dry. With this shift in approach, the originally proposed automatic calibration feature is not needed and was not pursued further.

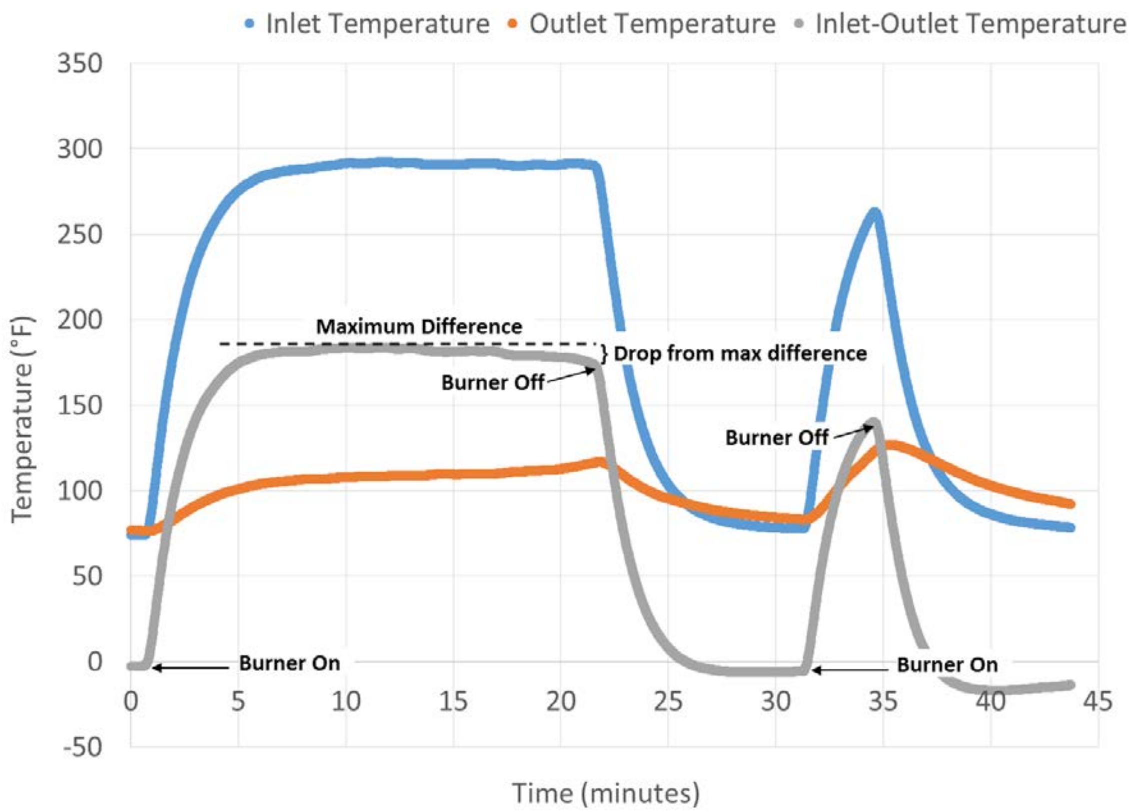

Figure 7 - Initial Comparison of Inlet to Outlet Temperatures

Correlation of Change of Temperature Difference to Remaining Moisture

A set of 13 tests was run to experimentally evaluate the correlation between the remaining water content of the load and a selected threshold, where the threshold is the percentage drop from the maximum difference temperature signal (Figure 7, gray line). The tests used a set of varied rags (mix of cotton-blend t-shirt, corduroy, and denim) sized approximately 1’-1.5’ squares. The tests varied the average room temperature, total load weight, and water weight (based on the spin-speed of the washing machine) (Table 3). The average room relative humidity was reported, but not controlled.

The results show that as the drying process continues, the absolute remaining water in the load in lbs converged as the threshold increased (Figure 8). When the inlet-outlet temperature difference dropped to 5% less than its maximum value, the remaining moisture for twelve tests was less than 0.5lb, meaning the load is “nearly dry”. This result held true for varying load sizes, initial water weight, and room temperature conditions. The one outlier was an artifact of noise in the inlet-outlet signal that resulted in a high maximum value. Signal processing methods can continue to be refined to reduce these errors. This finding suggests that the 5% threshold can be used to define a point when the load has at most 0.5lb of water remaining with reasonable accuracy.

The absolute load size greatly affects the percent remaining moisture content (RMC) calculation at the "nearly dry" point when 0.5lb of water remains. RMC is defined as the remaining water weight divided by the bone dry weight of the load. For example, when 0.5lb of water remains in a load that weighs 10lb when dry, the RMC is 5%. When 0.5lb of water remains in a load that weighs 2lb when dry, the RMC is 25%. Therefore, determining when 0.5lb of water remains does not provide a complete solution for the control algorithm because the goal is to dry to 2% remaining moisture content (RMC). This means that a measurement of the load size is needed to predict how much absolute remaining moisture is allowable to reach an RMC of 2%.

Table 3 – Calculated remaining water weight (lb) and remaining moisture content (%) for 13 tests when the inlet-outlet temperature difference dropped to 5% less than its maximum value

Test Properties					Calculated Results at 5% Threshold Value	
Test #	Average Room Temp (°F)	Average Room Relative Humidity (%)	Initial Load Weight with Water(lb)	Bone Dry Load Weight (lb)	Calculated Remaining Water Weight (lb)	Remaining Moisture Content (%)
1	75.1	45.8	11.626	7.807	.26	3.36
2	75.2	44.6	11.664	7.807	.37	4.73
3	75.2	40.4	11.601	7.807	.40	5.12
4	67.4	66.6	14.628	9.751	.34	3.49
5	88.2	42.4	14.702	9.751	.43	4.41
6	71.2	28.2	11.630	7.831	.42	5.36
7	66.5	46.0	14.628	9.751	.79	8.10
8	67.3	49.6	11.639	7.807	.30	3.84
9	75.1	24.9	14.674	9.763	.21	2.15
10	67.5	30.7	11.624	7.818	.40	5.12
11	75.4	23.4	12.989	7.818	.41	5.24
12	75.2	40.8	12.899	7.814	.39	4.99

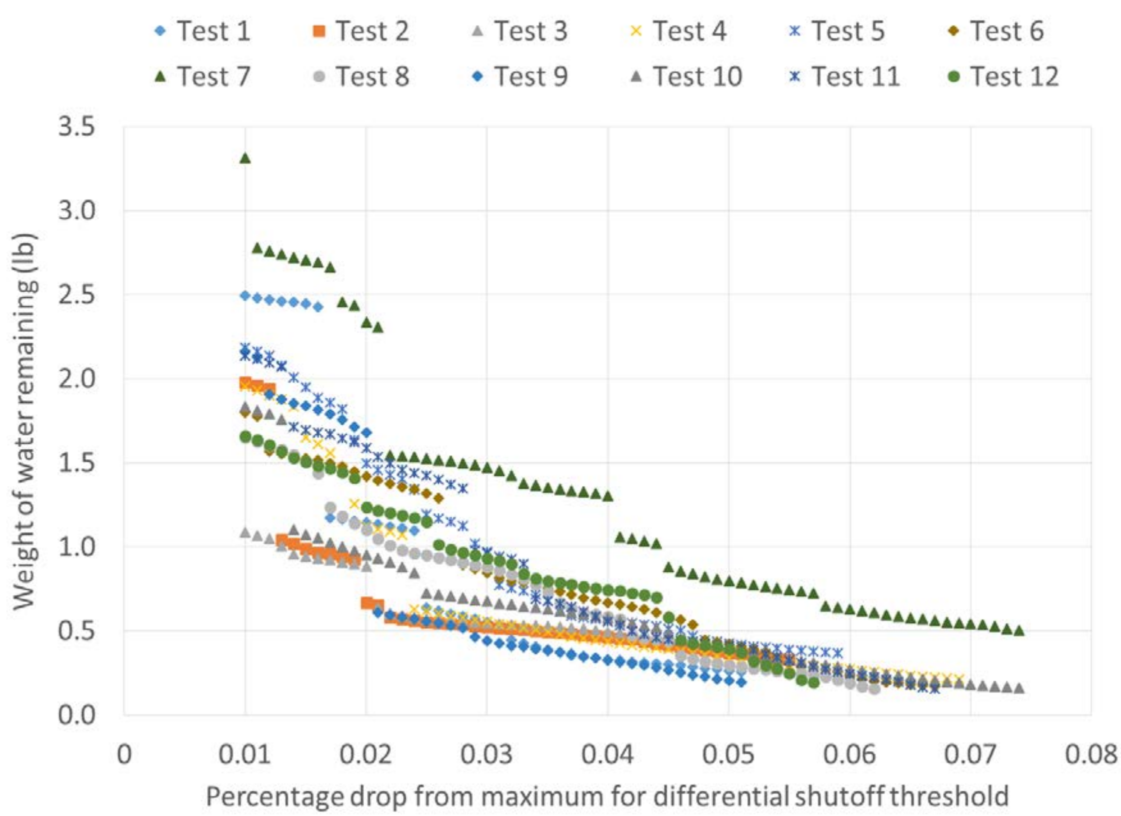

Figure 8 – Convergence of the absolute remaining water in the load as the percentage drop from maximum temperature differential increases.

Correlation of Temperature Response to Load Size

The research team shifted focus to determine a method to estimate the total weight of the load so that remaining moisture content could be calculated when the "nearly dry" signal was reached. It was theorized that the temperature response of the dryer to the firing of the burner would indicate the size of the load because a larger load has a higher capacity to absorb heat, which reduces the rate of heating. A strategy was tested to measure the load size by allowing the contents to first cool after the "nearly dry" point was reached, followed by firing the burner one more time to determine load size and calculate the remaining drying time required.

The data already obtained from the 12 tests listed in Table 3 plus four additional tests where the test rags were dry and one test where the dryer was empty were used to determine a correlation (Table 4, rows 1-16). A second order polynomial best fit correlated the maximum rate of temperature change metric to the mass of the dryer drum contents at the initial firing of the burner (Figure 9, blue). Through further testing, the research team found that this correlation was consistently over-predicting the drum contents mass during the second firing of the burner. Four additional tests (Table 4, rows 17-20) were run using the same mixed rags where the burner was re-fired after the "nearly dry" threshold was triggered and cool down period was satisfied (orange). The "nearly dry" correlation is slightly different from the "initial" firing correlation measurement because the dryer is not at room temperature on the second firing.

Due to time constraints, testing in this area was limited. In future research, the researchers intend to collect more data on these correlations. However, the data collected was sufficient to program the control algorithm and test the performance of the controller.

In developing this capability, the researchers realized that having a method to estimate the mass of the dryer contents at different times could provide other useful information. A measurement of the initial weight and the "nearly dry" weight, combined with the drying time, could be used to estimate real time energy metrics for the dryer. This information, tracked over time, could be used as fault detection to alert the user if the dryer performance falls out of the expected range (indicating, for example, blocked exhaust ducts or clogged lint traps). The efficiency information could also be used to provide feedback to the user to encourage them to dry larger loads by showing improved efficiency under these conditions. An analogy to this is showing real-time fuel consumption to vehicle drivers. In theory, drivers may change behavior if shown in real-time that driving faster on freeways decreases miles driven per gallon of fuel. This idea is a tangent to the research objective that was not thoroughly investigated and is a possible area for future research.

Table 4 – Summary of tests used for correlation of maximum rate of change metric to load weight for both the initial and almost dry measurement

Test Properties						
Test #	Contents	Average Room Temp (°F)	Average Room Relative Humidity (%)	Initial Load Weight with Water(lb)	Bone Dry Load Weight (lb)	Max rate of change metric
1	Mixed Rags	75.1	45.8	11.626	7.807	0.12
2	Mixed Rags	75.2	44.6	11.664	7.807	0.13
3	Mixed Rags	75.2	40.4	11.601	7.807	0.14
4	Mixed Rags	67.4	66.6	14.628	9.751	0.08
5	Mixed Rags	88.2	42.4	14.702	9.751	0.09
6	Mixed Rags	71.2	28.2	11.630	7.831	0.12
7	Mixed Rags	66.5	46.0	14.628	9.751	0.09
8	Mixed Rags	67.3	49.6	11.639	7.807	0.12
9	Mixed Rags	75.1	24.9	14.674	9.763	0.09
10	Mixed Rags	67.5	30.7	11.624	7.818	0.11
11	Mixed Rags	75.4	23.4	12.989	7.818	0.10
12	Mixed Rags	75.2	40.8	12.899	7.814	0.10
13	Mixed Rags	75.2	48.2	9.791	9.791	0.18
14	Mixed Rags	75.2	46.6	5.352	5.352	0.28
15	Mixed Rags	76.9	22.5	7.824	7.824	0.22
16	Mixed Rags	75.0	33.4	0	0	0.55
17	Mixed Rags	74.7	47.6	6.753	6.753	0.19
18	Mixed Rags	74.5	47.8	5.817	5.817	0.22
19	Mixed Rags	74.4	47.4	9.1134	9.1134	0.16
20	Mixed Rags	74.6	47.5	0	0	0.50

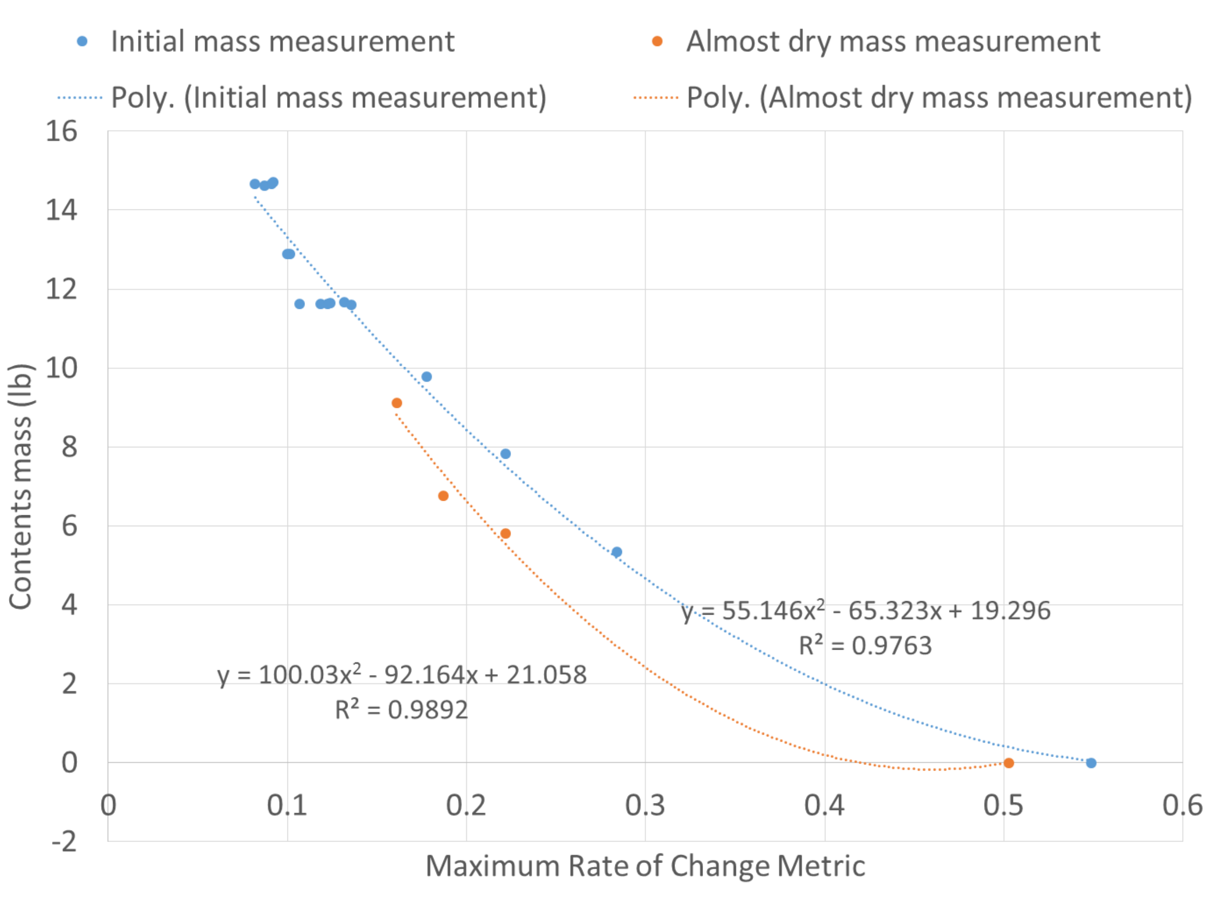

Figure 9 – Mass measurement correlation for initial and almost dry measurements

Summary of Control Algorithm Design

The final control algorithm design combined the correlation of change of temperature difference to remaining moisture and the correlation of temperature response to load size. With these two pieces of information, the percent remaining moisture content can be predicted and the remaining drying time after the "nearly dry" threshold is reached can be calculated. The algorithm was programmed and tested, and the results with respect to the five research objectives are presented.

Objective 1: Confirm hardware measures differential temperature signal with an accuracy of 0.5°F.

This objective was originally written with the expectation that when the load was dry or near dry, the differential outlet-inlet temperature would approach zero and that measurement accuracy near zero would be very important. However, as described in the results section "Initial Comparison of Inlet to Outlet Temperature," heat losses from the drum and infiltration into the drum resulted in a temperature difference that is on the order of 180°F (Figure 7). As described in the results section "Correlation of Change of Temperature Difference to Remaining

Moisture," the revised control approach looks for a drop of 5% in the maximum temperature difference, which equates to a change in the differential temperature of approximately 9°F. Furthermore, because the control scheme measures the maximum difference and drop from the maximum difference, the actual accuracy of the measured values are not critical. Therefore, the 0.5°F signal accuracy is not a requirement for the controller based on the revised approach. Any resistive type temperature sensor (such as thermistor or RTD) with typical accuracy (1-2°F) for these sensor types should suffice.

Objective 2: Confirm test stand is capable of testing dryer to specifications of DOE Appendix D2.

The test stand was constructed to meet the testing protocol requirements of DOE Appendix D2 [3] (Figure 3). There were requirements that were not met because the cost and complexity of meeting these requirements was not justified for testing the automatic termination controller. The most relevant requirements for the test protocol are summarized here, including any deviation from the test standard.

1. Installation. The dryer was installed according to the manufacturer's instructions. Instead of the exhaust simulator as described in the test standard, an exhaust duct of 4" diameter and 11' long with 2-90° elbows was installed to exhaust the air from the dryer to the outdoors, which was required for safety in the laboratory. The exhaust simulator is designed to simulate a 4" exhaust duct 8' long with 2-90° elbows and a standard weather hood. Because the actual exhaust ducting is similar to what the simulator is designed to represent, this change was not expected to impact the test results.
2. Ambient temperature and humidity. The chamber was able to maintain ambient air temperature at 75 ± 3°F and room relative humidity of 50 ± 10% as required by the test standard (Figure 10).
3. Electrical supply. The electrical supply was not regulated due to cost constraints. The electricity was provided by the utility, Pacific Gas and Electric (PG&E), to the building.
4. Gas Supply. The gas supply to the dryer was regulated through an adjustable gas pressure regulator to meet the pressure requirement of the dryer of 3.5-5 inwc. The natural gas used was supplied by PG&E and the heating value of the gas supply was obtained from the PG&E website for geographic location "P07", which was updated weekly [6]. The heating value of the fuel was between 1036-1042 Btus per standard cubic foot. In order to present the results conservatively, all natural gas energy consumption results were calculated with an assumed fuel heating value of 1042 Btu/hr. Actual heating energy use may be slightly less (<1%).
5. Instrumentation
    a. Weighing scale for test cloth. The scale used met the resolution and accuracy of the test standard (Table 2).

b. Kilowatt-hour meter. The killowatt-hour meter used met the resolution and accuracy requirement of the test standard (Table 2).
c. Gas meter. The gas meter accuracy was close to that required by the test standard. The accuracy of the meter was 0.7% of the reading in comparison to the 0.5% required by the standard (Table 2). The resolution of the meter exceeded the requirement of the test standard.
d. Dry bulb and wet bulb psychrometer. The dry bulb and wet bulb psychrometer met the accuracy requirement of the test standard (Table 2).
e. Temperature. The temperature sensors met the accuracy required by the test standard (Table 2).

6. Lint trap. The lint trap was cleaned after each test as required by the test standard.
7. Test Cloths. The energy tests cloths used met the requirements of the test standard. The test cloth preconditioning varied slightly from the test standard in that tap water was used to wash the load (instead of softened water) and the tap water was room temperature (instead of heated as required by the standard). The impact of the wash water temperature and hardness is not expected to impact the test results, so the cost to modify the lab to pre-condition the wash water was not justified. The mass of the test cloths, the amount of water added to the test cloths, and the loading of the test cloths into the dryer all followed the test standard.

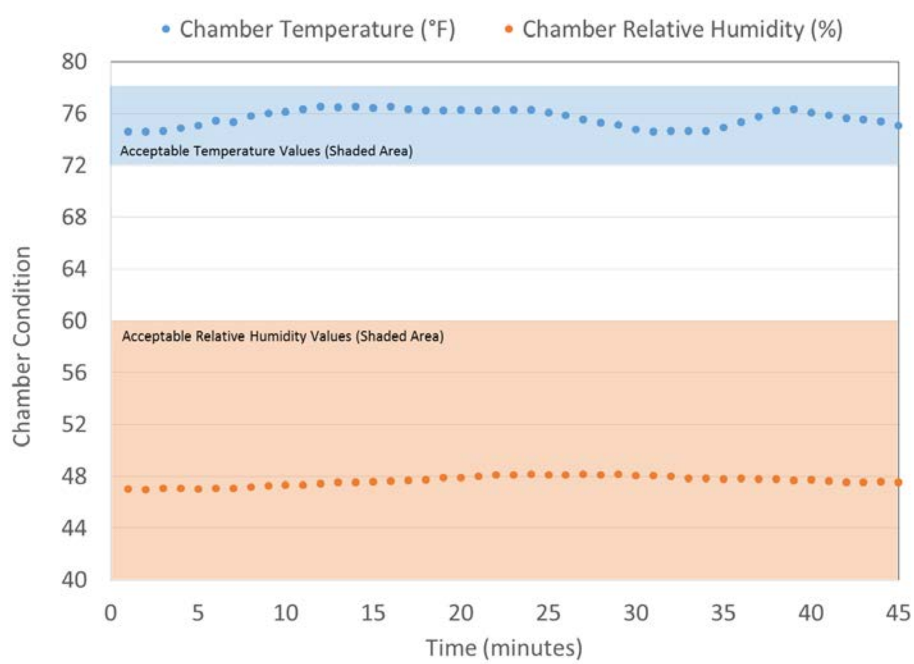

Figure 10 – Chamber temperature and relative humidity control during example DOE test.

Objective 3 and Objective 4: Demonstrate control shuts off gas heat within two minutes when remaining moisture content is 2% or less and demonstrate energy

consumption using auto shut-off as measured by DOE Appendix D2 is of 2.6kWh or less.

Tested Control Algorithm

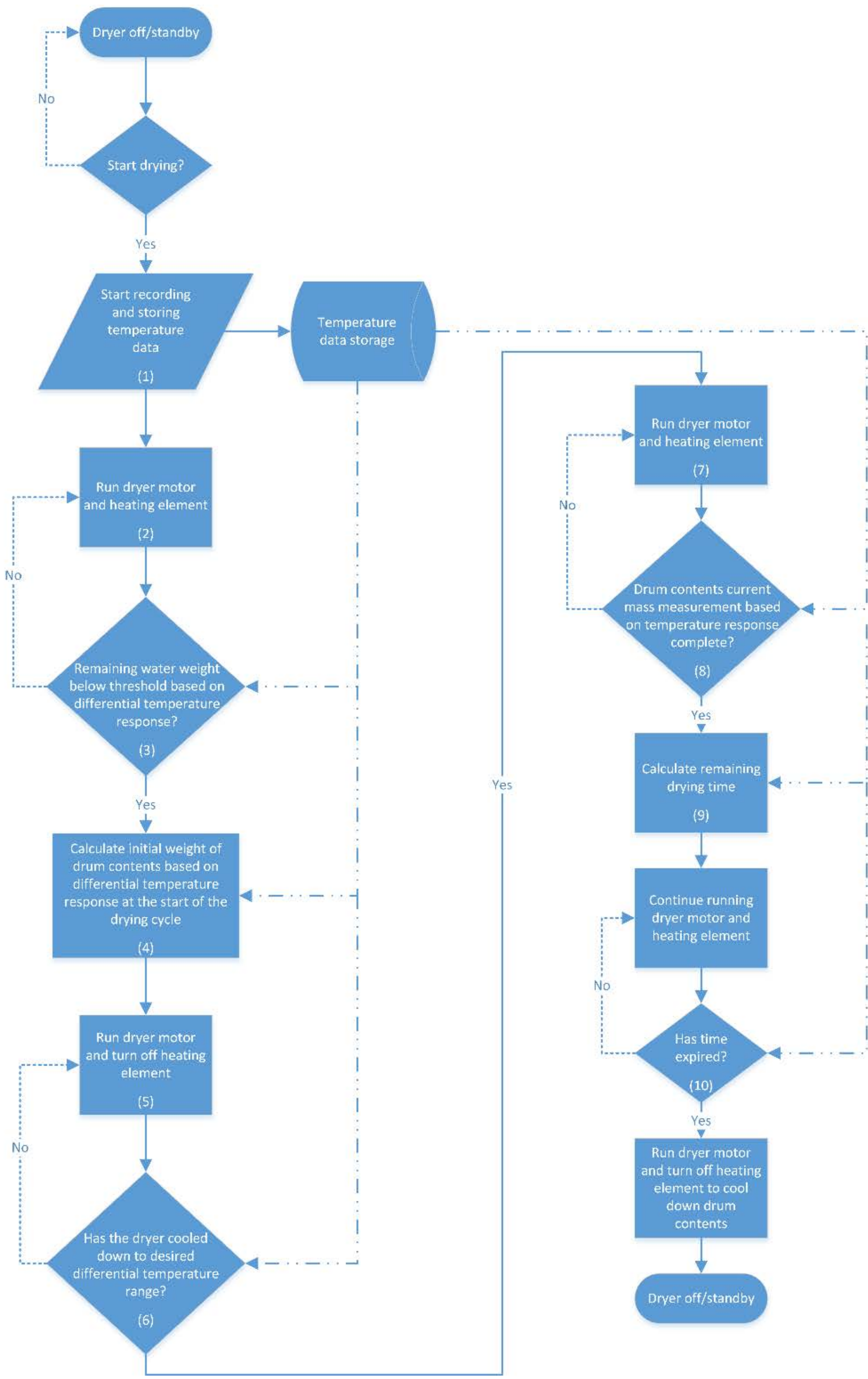

Figure 11 illustrates the steps for controlling clothes drying operations. When the drying cycle is commenced, the temperature data is recorded and stored (block 1). Both the motor for the drum and fan (blower) as well as heating element of the dryer are activated (block 2). A determination is made for the "state of dryness" of the clothing (block 3). It is determined if the amount of water remaining on the clothing (e.g., water weight) is below a given threshold. The amount of water remaining is estimated based on the temperature differences which are calculated from the stored temperature data. If this evaporative state has not yet attained a threshold level of "dryness," then execution returns again to block 2. Otherwise, the clothes have reached a target level of dryness for the remaining weight of water, wherein additional testing is performed to determine the percent remaining moisture content based on the weight of the water remaining and the predicted weight of the dry load.

Next, an estimation is made of the initial mass of the drum contents. The estimation is made based on the maximum rate of change relationship, with respect to time, between the inlet and outlet temperatures, calculated from the stored temperature data (block 4). The motor for the drum and fan (blower) continues running with the heating element turned off (block 5). A determination is made if the dryer has cooled down to a desired differential temperature range (block 6). The contents are cooled down so the system can re-measure the weight of the load by measuring a time response to it being heated again. If it has not sufficiently cooled-down, then execution returns to block 5, otherwise execution continues at block 7.

At block 7, the heating element turns back on to re-measure the load, which is known to be nearly dry. A check is made at block 8 to determine if the temperature response profile for re-measurement of the load is complete. If the temperature response profile is not complete, then execution returns to block 7 with motor and heater still on. Otherwise, the response profile is complete and is utilized in block 9 to accurately determine the remaining drying time to reach the desired percent remaining moisture content. The drum motor and heater then continue in use for the determined period, such as seen with periodic checks for time expiration (block 10). Upon determining the end of the time period, the heater is turned off while drum motor continues in operation to cool down the drum contents for a desired period of time and/or temperature level. Then, the dryer is turned-off or put into standby mode.

Figure 12 illustrates an example of a drying cycle for the differential temperature dryer cycle controller, showing a plot of temperature difference (between inlet air temperature and the temperature of outlet air) over time in an upper curve and an on/off status of the dryer shown as blocks over the respective regions of the plot. In this plot, references are made to

associated step numbers depicted in

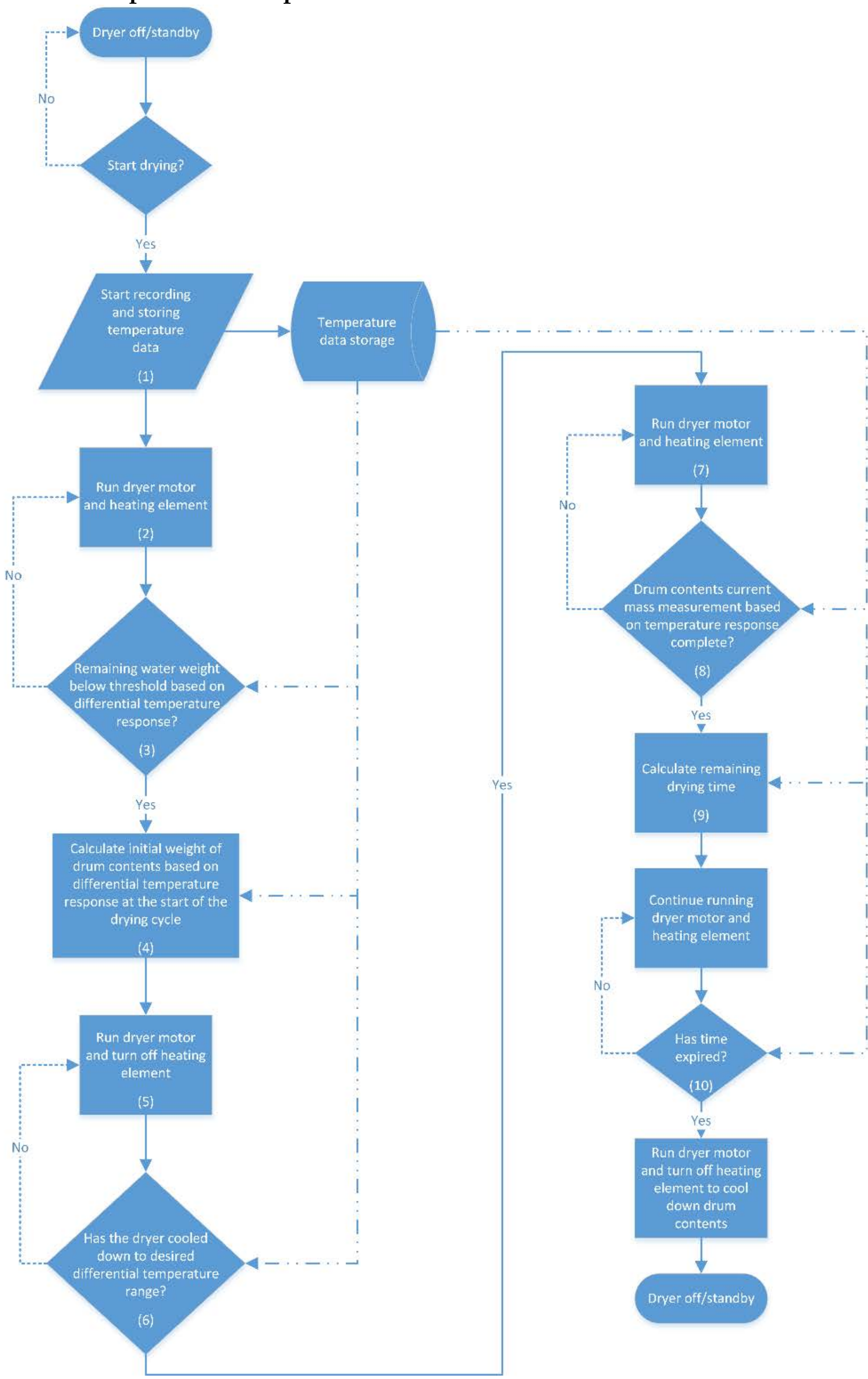

Figure 11. At the far left, the dryer cycle commences (blocks 1, 2), and after a short period of time an estimation is made (block 4) of the initial drum contents based on rate of temperature differential change. Drying is seen continuing to a point (block 3) at which the amount of remaining water on the clothing is considered to have dropped to a selected threshold, at which time the heating element is switched off to enter a cooling phase, until the temperature of the drum contents is below a threshold (block 6), at which time the heater elements and drum motor commence running again (block 7). As the drum contents heat up again, an estimation is performed to determine remaining drying time (block 9), with drying continuing until a determination that this time period has expired, upon which the heating element is switched off while the drum motor runs. Then after the clothing is sufficiently cooled, the dryer is turned off or put into standby mode.

Remaining Moisture Content and Energy Consumption Results

The remaining moisture content and energy consumption results for the automatic termination dryer controller are described in Table 5. For the DOE test load, a load with 2% remaining moisture content would weigh 8.6 lb. For three repeats of the DOE Appendix D2 test, the final weight of the dry load when the controller shut-off the dryer was 8.568 lb, 8.591 lb, and 8.595 lb, which equates to a remaining moisture content of 1.62%, 1.89%, and 1.93% respectively. The measured evaporation rate near the end of the cycle was 0.005 lbw/second, meaning that the controller shut off the dryer within 7 seconds of reaching a remaining moisture content of 2%. The total energy consumption (converted to kWh) for each load was: 2.80, 2.69 and 2.61 kWh (average: 2.70 kWh). This is 4% higher than the target objective of the project: 2.6 kWh.

The research team ran 16 additional tests evaluating the controller over a variety of conditions in which room temperature conditions were varied and load type and size were varied (Table 5). The results of 15 tests are presented: one test was excluded because a large amount of lint was collected in the drying process which affected the ability to accurately weigh load at the end of the test. For all 18 tests presented, the results varied between 1.62 - 6.68% remaining moisture content. All but one test had a remaining moisture content between 1.62 - 5%, where 5% is higher than the DOE test standard of 2%, however, would still be considered by consumers as “dry”. The energy consumed for the drying cycles varied between 1.40-4.13 kWh, where the energy consumption was a function of the size and composition of the load.

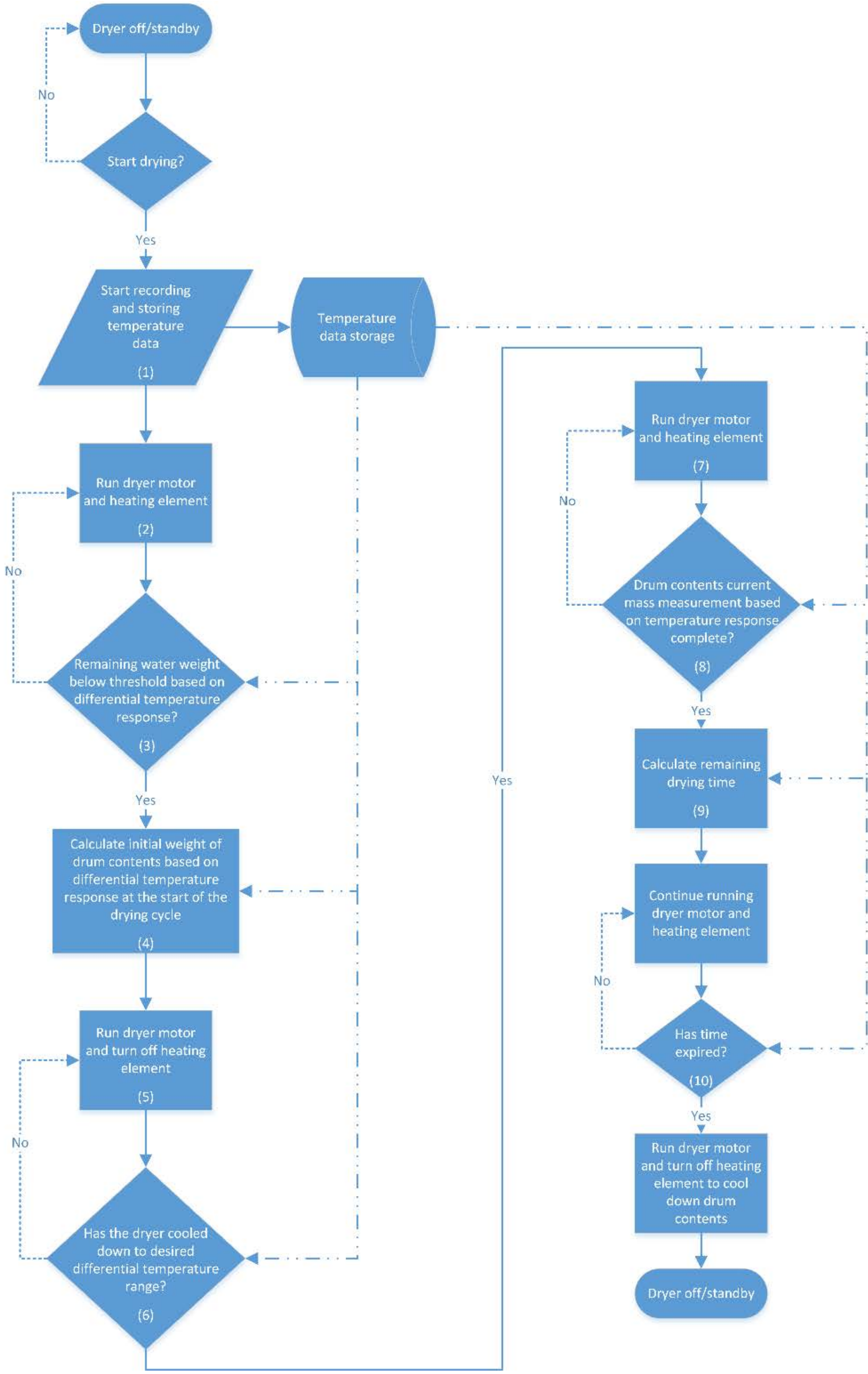

Figure 11 - Logic diagram for controller

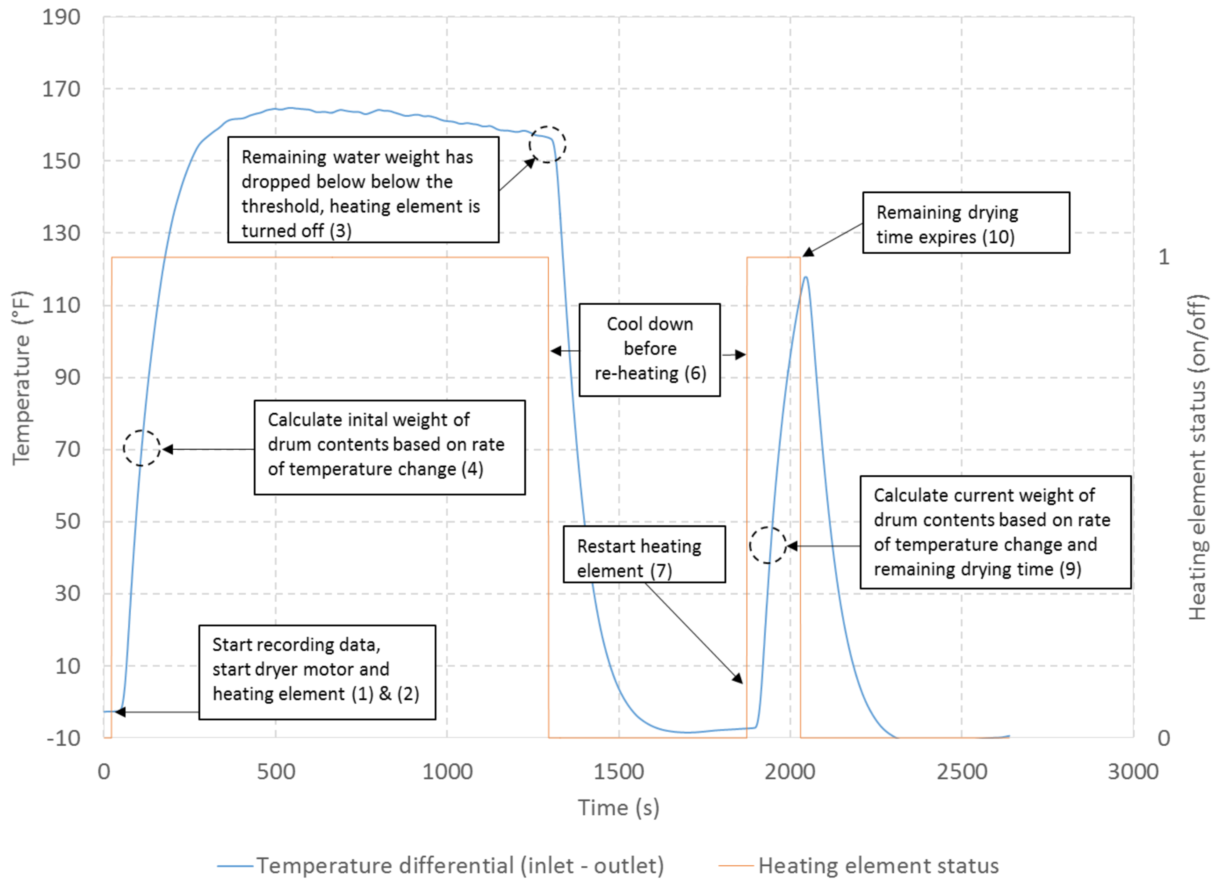

Figure 12 - Example Drying Cycle Using Temperature Differential Method

Table 5 – Remaining Moisture and Energy Performance Metrics for Dryer Controller[TEP1]

		Test Chamber Properties						Test Load Meaurements						Dryer Measurements				Predicted	
		Temperature			Relative Humidity			Pre-Test			Post-Test								
Test #	Description of load	AVG (°F)	MAX (°F)	MIN (°F)	AVG (%)	MAX (%)	MIN (%)	Pre-Test Bone Dry Weight (lb)	Pre-Test Water Weight (lb)	Pre-Test Initial Weight (lb)	Post-Test Dry Weight (lb)	Water removed (lb)	*Post-test RMC (%)*	Cycle length (min)	Natural Gas (kWh)	Electricity (kWh)	Energy Total (kWh)	Predicted Dry Weight (lb)	Predicted Final RMC (%)
21	DOE Test Cloths	75.1	76.5	73.6	47.2	51.5	43.2	8.432	4.867	13.299	8.568	4.730	***1.62%***	42.05	2.622	0.182	***2.804***	8.941	2%
22	DOE Test Cloths	75.7	77.5	74.1	48.3	52.7	44.7	8.432	4.848	13.280	8.591	4.689	***1.89%***	41.77	2.504	0.183	***2.688***	9.856	2%
23	DOE Test Cloths	75.1	76.7	73.5	45.3	50.6	41.7	8.432	4.875	13.307	8.595	4.712	***1.93%***	41.72	2.425	0.185	***2.610***	9.589	2%
24	Two heavy sweatshirts	75.6	77.7	74.0	38.2	41.7	34.4	2.003	0.781	2.784	2.045	0.739	***2.11%***	31.27	1.618	0.132	***1.751***	0.051	2%
25	Three shells and insulated jacket	75.7	77.5	74.2	40.7	45.8	37.3	5.788	1.289	7.078	5.864	1.214	***1.31%***	28.95	1.269	0.126	***1.395***	3.293	2%
26	Shells jackets, fleece, sweatshirts	75.0	76.1	73.6	45.6	51.2	42.1	9.507	1.868	11.375	9.658	1.716	***1.59%***	30.70	1.444	0.137	***1.581***	7.308	2%
27	Cotton towels load 1	75.7	82.1	73.5	34.7	38.2	27.4	9.643	6.430	16.073	9.845	6.227	***2.10%***	57.70	3.869	0.263	***4.132***	8.020	2%
28	Cotton towels load 2	75.8	78.1	73.8	34.5	38.3	30.3	4.826	3.167	7.992	5.148	2.844	***6.68%***	37.78	2.042	0.171	***2.213***	3.574	2%
29	Cotton towels load 3	79.0	90.7	74.3	27.8	34.3	18.2	7.245	4.761	12.006	7.511	4.495	***3.68%***	43.28	2.612	0.192	***2.804***	4.961	2%
30	Sheet, kids clothes	75.8	78.3	74.1	30.8	37.6	24.0	7.535	3.797	11.332	7.856	3.476	***4.26%***	38.52	2.123	0.172	***2.295***	6.076	2%
31	Cloth rags 1	75.3	78.0	73.8	37.9	47.5	33.5	5.652	2.829	8.480	5.904	2.577	***4.46%***	34.68	1.799	0.152	***1.951***	5.784	2%
32	Cloth rags 2	75.0	75.8	73.9	34.1	38.3	28.7	6.557	3.531	10.088	6.821	3.267	***4.03%***	36.65	1.970	0.169	***2.139***	7.329	2%
33	Cloth rags 3	75.3	76.5	74.1	31.7	35.9	27.9	8.866	4.699	13.564	9.185	4.380	***3.60%***	40.45	2.396	0.187	***2.583***	9.919	2%
34	Cloth rags 4	78.4	80.6	76.4	54.1	56.6	51.7	5.652	2.871	8.522	5.924	2.598	***4.83%***	34.67	1.847	0.154	***2.002***	6.637	2%
35	Cloth rags 5 (Humid)	76.7	79.8	73.9	62.2	66.7	58.2	6.557	3.474	10.031	6.803	3.228	***3.75%***	41.93	2.382	0.186	***2.567***	7.704	2%
36	Cloth rags 6 (Humid)	76.1	78.2	73.6	61.7	65.4	58.1	8.866	4.758	13.623	9.158	4.465	***3.30%***	43.20	2.846	0.220	***3.066***	9.376	2%
37	Cloth rags 7 (Hot)	90.3	91.7	88.5	24.1	26.0	22.3	8.866	4.624	13.490	9.006	4.484	***1.58%***	40.02	2.322	0.182	***2.504***	9.405	2%
38	Cloth rags 8 (Hot)	90.3	91.4	88.6	24.6	27.3	22.1	6.557	3.528	10.085	6.750	3.335	***2.94%***	37.37	1.955	0.167	***2.122***	7.538	2%

Objective 5: Confirm sensors and controller can be manufactured at a cost not to exceed $25 to the dryer manufacturer.

Figure 13 illustrates a design for a controller capable of running the designed algorithm. The components shown are the following:

- U1 – Microcontroller
- U2 – EEPROM memory
- U3 – Analog to digital converter
- U4 – DC/DC Converter (24V – 3.3V)
- Y1 – Clock for microcontroller
- Kx – Output relays
- Rx, Cx – Various resistors and capacitors need for the circuit

The estimated cost breakdown for 10,000 units (Table 6) is estimated at $24, which is less than the $25 target cost. Additionally, the output relays and power supply may be redundant with components used in existing dryer controllers, so that the incremental cost over existing controllers may be substantially less.

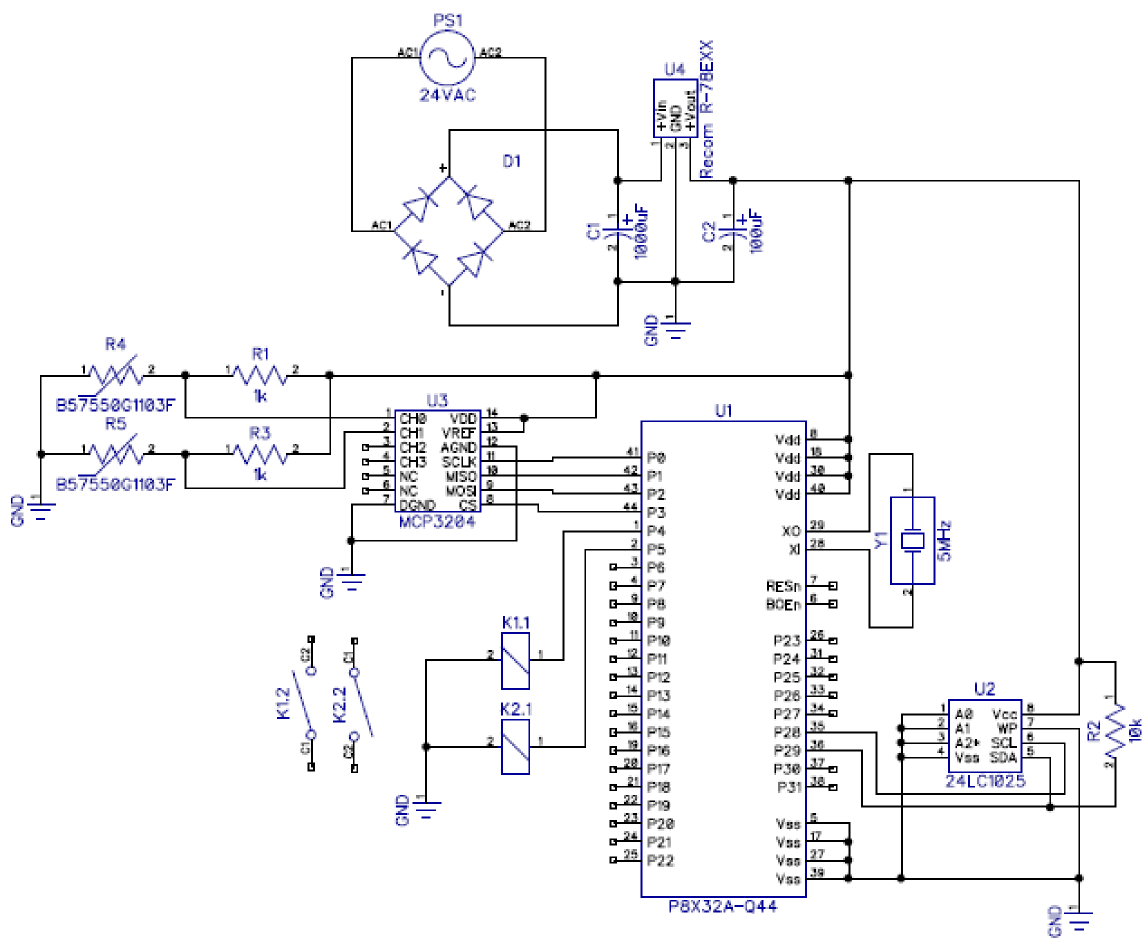

Figure 13 - Controller design circuit schematic

Table 6 - Controller cost breakdown

Component	Quantity	Bulk cost		
Main unit				
Microcontroller (32 bit)	1	$7.480		
Analog to digital converter (12 bit)	1	$2.460		
Clock (5 MHz)	1	$0.330		
EEPROM (1Mbit)	1	$2.670		
EEPROM resistor	1	$0.001		
Output relay	2	$5.692		
Temperature sensor and components				
•Thermistor	2	$2.600		
• Additional resistor	2	$0.001		
Power supply (based on having 24Vac)				
• Rectifier	1	$0.093		
• DC/DC converter	1	$2.430		
• 100 uF capacitor	1	$0.056		
• 1000 uF capacitor	1	$0.176	Total:	$23.99

Conclusions

An automatic dryer cycle termination controller was developed that met the energy efficiency and performance objectives of this project. The conclusions with respect to the specific objectives of the project are summarized in

Table 7. For the DOE test load, a load with 2% remaining moisture content would weigh 8.6 lb. For three repeats of the DOE Appendix D2 test, the final weight of the dry load when the controller shut-off the dryer was 8.568 lb, 8.591 lb, and 8.595 lb, which equates to a remaining moisture content of 1.62%, 1.89%, and 1.93% respectively. The measured evaporation rate near the end of the cycle was 0.005 lbw/second, meaning that the controller shut off the dryer within 7 seconds of reaching a remaining moisture content of 2%. The total energy consumption (converted to kWh) for each load was: 2.80, 2.69 and 2.61 kWh (average: 2.70 kWh). This is 4% higher than the target objective of the project: 2.6 kWh. In comparison to test data for three other cycle termination controllers tested by the DOE that had results of 2.91, 3.16, and 2.84 kWh (average 2.97 kWh) [3], the controller design in this project indicates a savings of 5-15%, which is below the 20% goal set for the project. It should be noted that the expected energy savings would be greater under real world, variable test conditions.

In addition to the DOE Appendix D2 tests, the researchers tested the controller with a variety of different load types with different room air conditions. The controller automatically shut off the dryer when the load was determined to be dry, and the measured remaining moisture content at the end of the tests varied between 1.62 - 6.68%. All but one test had a remaining moisture content between 1.62 - 5%, where 5% is higher than the DOE test standard of 2%, however, would still be considered by consumers as "dry". The energy consumed for the drying cycles varied between 1.4 and 4.13 kWh, where the energy consumption was a function of the size and composition of the load.

In summary, the controller provides the following advantages over existing dryer control systems:

1. The temperature difference sensing technology is not impacted by specific inlet air conditions.
2. Sensors can be configured so that actual contact is not necessary between dryer contents and the sensor(s).
3. The sensor and controller can estimate average moisture content (dryness) of the contents of the dryer instead of relying on sensing only items that intermittently come into contact with the sensor.
4. The data used to determine when to terminate the drying cycle can also be used to provide energy efficiency reporting metrics.

The researchers have filed for a patent protecting the intellectual property contained in this technology and plan to market the technology to dryer manufacturers under a licensing agreement.

Table 7 - Summary of conclusions by objective

Objective	Conclusions
1. Confirm hardware measures differential temperature signal with an accuracy of 0.5°F.	The control scheme was revised to measure the maximum difference and drop from the maximum difference, the actual accuracy of the measured values are not critical. Therefore, the 0.5°F signal accuracy is not a requirement for the controller based on the revised approach. Any resistive type temperature sensor (such as thermistor or RTD) with typical accuracy (1-2°F) for these sensor types should suffice.
2. Confirm test stand is capable of testing dryer to specifications of DOE Appendix D2.	Test stand was constructed to largely satisfy the requirements of DOE Appendix D2. Researchers used utility provided natural gas instead of laboratory grade natural gas, and accounted for this by using the highest heating value of the fuel reported by the utility providing the gas service (which was 1.7% higher than the heating value specified by the test standard). Also, it was not possible to condition the tests cloths with the specific water temperature and hardness, however, the researchers expect this will have no impact on the results.
3. Demonstrate control shuts off gas heat within two minutes when remaining moisture content is 2% or less	For the DOE test load, a load with 2% remaining moisture content would weigh 8.6 lb. For three repeats of the DOE Appendix D2 test, the final weight of the dry load when the controller shut-off the dryer was 8.568 lb, 8.591 lb, and 8.595 lb, which equates to a remaining moisture content of 1.62%, 1.89%, and 1.93% respectively. The measured evaporation rate near the end of the cycle was 0.005 lbw/second, meaning that the controller shut off the dryer within 7 seconds of reaching a remaining moisture content of 2%.
4. Demonstrate energy consumption using auto shut-off as measured by DOE Appendix D2 is of 2.6 kWh or less (estimated 20% savings or 0.4 kWh per load).	The total energy consumption (converted to kWh) for each of three repeat DOE Appendix D2 tests was: 2.80, 2.69 and 2.61 kWh (average: 2.70 kWh). This is 4% higher than the target objective of the project: 2.6 kWh.
5. Objective 5: Confirm sensors and controller can be manufactured at a cost not to exceed $25 to the dryer manufacturer.	The estimated cost breakdown for 10,000 units (Table 6) is estimated at $24 per unit, which is less than the $25 target cost. Additionally, the output relays and power supply may be redundant with components used in existing dryer controllers, so that the incremental cost over existing controllers may be substantially less.

Recommendations

The technology developed from this project shows significant promise and, as a result, the researchers have filed for intellectual property protection. The University intends to pursue licensing of the technology to a dryer manufacturer, which is the most practical path forward for the technology. The researchers have made initial steps to secure additional funding from a California utility to test the concept in electric dryers, where it is expected that the same principles would apply. Further research to support commercialization could include:

6. Additional data correlating the load size to the temperature response of the dryer when the burner fires
7. Improving signal processing techniques in order to reduce errors in calculating the maximum temperature difference and associated drop of the temperature difference when the load is "nearly dry"
8. Testing the controller in different models and brands of dryers
9. Testing the controller in comparison to other existing controllers under load and room conditions that vary from the DOE Appendix D2 standard
10. Exploring calculation and application of real-time energy efficiency tracking metrics (This was not an objective of this project, but an interesting idea that was conceived toward the end of the project and is worthy of additional investigation.)

Public Benefits to California

In this project, the controller demonstrated a cycle efficiency of 2.70 kWh per load using the DOE Appendix D2 test procedure. This is in comparison to test data for three other cycle termination controllers tested by the DOE that had results of 2.91, 3.16, and 2.84 kWh (average 2.97 kWh) [3]. The performance of the controller design in this project in comparison to the three controllers tested by DOE indicates a savings of 5-15%. Even larger savings are expected under test conditions that vary from the DOE Appendix D2 test procedure, and this is an area indicated for future research. Potential energy savings from possible development of energy efficiency reporting metrics for fault detection and/or influencing user behavior are also possible. A 10% savings estimate is a conservative estimate from which the possible benefits to deploying this controller in California can be calculated.

According to the California Energy Commission's 2009 Residential Appliance saturation survey, gas dryers consume 6% of total residential natural gas use [1]. Residential natural gas use consumes 4,854 million therms in California per year [7]. Based on this data, residential gas dryers consume 291 million therms per year. Saving 10% of dryer natural gas use with 10% penetration equates to approximately 3 million therms per year (or $3 million per year to California residents, assuming an end-use natural gas price of $1 per year). This equates to approximately 35,000 tons of carbon dioxide equivalent greenhouse gas emissions per year [8]. Additional savings are expected over time in commercial environments with dryers (such as hotels, laundromats, athletic clubs, etc).

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California Energy Commission Energy Innovations Small Grant (EISG) Program PROJECT DEVELOPMENT STATUS	**Questionnaire**

Answer each question below and provide brief comments where appropriate to clarify status. If you are filling out this form in MS Word the comment block will expand to accommodate inserted text.

Please Identify yourself, and your project: **PI Name** _Theresa Pistochini_ **Grant** # _57995A/14-04G	
Overall Status	
Questions	Comments:
1) Do you consider that this research project proved the feasibility of your concept?	Yes. Controller performance met objectives and was demonstrated in a variety of other conditions.
2) Do you intend to continue this development effort towards commercialization?	Yes, through a licensing path.
Engineering/Technical	
3) What are the key remaining technical or engineering obstacles that prevent product demonstration?	No major obstacles are known. Demonstration in additional dryers, including electric would be helpful. Improving accuracy of weight measurement would enable additional features and interest the technology.
4) Have you defined a development path from where you are to product demonstration?	Planning to seek licensee (dryer manufacturer). Will seek funding for additional lab tests, and an actual use field demonstration if possible.
5) How many years are required to complete product development and demonstration?	1-2 years
6) How much money is required to complete engineering development and demonstration?	$50,000-$100,000
7) Do you have an engineering requirements specification for your potential product?	Yes, included in final report.
Marketing	
8) What market does your concept serve?	Residential (mainly)
9) What is the market need?	DOE reports that show residential dryer automatic cycle termination controllers perform poorly, tending toward over-drying and excess energy us.
10) Have you surveyed potential customers for interest in your product?	No, although to a consumer the algorithm would be invisible to a user used to an "auto-dry" function.

11) Have you performed a market analysis that takes external factors into consideration?	No detailed market analysis. However, we have been following developments related to federal appliance regulation and Energy Star testing, which are moving toward imposing performance requirements on automatic cycle termination controllers.
12) Have you identified any regulatory, institutional or legal barriers to product acceptance?	No
13) What is the size of the potential market in California for your proposed technology?	Residential natural gas use consumes 4,854 million therms in California per year [7]
14) Have you clearly identified the technology that can be patented?	Yes
15) Have you performed a patent search?	Both self search and professional search, there is some related IP. However, the technology appears to be unique.
16) Have you applied for patents?	Yes - 1
17) Have you secured any patents?	No, the application date was 6/30/2016.
18) Have you published any paper or publicly disclosed your concept in any way that would limit your ability to seek patent protection?	No
Commercialization Path	
19) Can your organization commercialize your product without partnering with another organization?	No. Dryer manufacturers are the logical partner.
20) Has an industrial or commercial company expressed interest in helping you take your technology to the market?	No, we have kept our developments confidential while proving the concept and seeking IP protection.
21) Have you developed a commercialization plan?	No
22) What are the commercialization risks?	Securing a licensee of the technology is the major hurdle/risk.
Financial Plan	

23) If you plan to continue development of your concept, do you have a plan for the required funding?	Yes. A California utility has expressed interest in continuing the development and testing the concept in electric dryers.
24) Have you identified funding requirements for each of the development and commercialization phases?	No
25) Have you received any follow-on funding or commitments to fund the follow-on work to this grant?	Yes – Sacramento Municipal Utility District ($35,000)
26) What are the go/no-go milestones in your commercialization plan?	N/A
27) How would you assess the financial risk of bringing this product/service to the market?	N/A
28) Have you developed a comprehensive business plan that incorporates the information requested in this questionnaire?	No
Public Benefits	
29) What sectors will receive the greatest benefits as a result of your concept?	Residential
30) Identify the relevant savings to California in terms of kWh, cost, reliability, safety, environment etc.	According to the California Energy Commission's 2009 Residential Appliance saturation survey, gas dryers consume 6% of total residential natural gas use [1]. Residential natural gas use consumes 4,854 million therms in California per year [7]. Based on this data, residential gas dryers consume 291 million therms per year. Saving 20% of dryer natural gas use with 10% penetration equates to approximately 6 million therms per year (or $6 million per year to California residents, assuming an end-use natural gas price of $1 per year). This equates to approximately 35,000 tons of carbon dioxide equivalent greenhouse gas emissions per year [8]. Additional savings are expected over time in commercial environments with dryers (such as hotels, laundromats, athletic clubs, etc).
31) Does the proposed technology reduce emissions from power generation?	No

32) Are there any potential negative effects from the application of this technology with regard to public safety, environment etc.?	No
Competitive Analysis	
33) What are the comparative advantages of your product (compared to your competition) and how relevant are they to your customers?	Energy savings, better performance, real-time energy reporting, and fault detection
34) What are the comparative disadvantages of your product (compared to your competition) and how relevant are they to your customers?	None known
Development Assistance	
The EISG Program may in the future provide follow-on services to selected Awardees that would assist them in obtaining follow-on funding from the full range of funding sources (i.e. Partners, PIER, NSF, SBIR, DOE etc.). The types of services offered could include: (1) intellectual property assessment; (2) market assessment; (3) business plan development etc.	
35) If selected, would you be interested in receiving development assistance?	Yes, connection with manufacturers interested in licensing the technology would be helpful.