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Residential Clothes Dryer Performance Under Timed and Automatic Cycle Termination Test Procedures

Kyle Gluesenkamp

October 2014

OAK RIDGE NATIONAL LABORATORY
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Energy and Transportation Science Division

RESIDENTIAL CLOTHES DRYER PERFORMANCE UNDER TIMED AND AUTOMATIC CYCLE TERMINATION TEST PROCEDURES

Kyle Gluesenkamp

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ABBREVIATIONS

1992	shorthand to refer to AHAM 1992 load
2009	shorthand to refer to AHAM 2009 load
A	amperes of electric current
AHAM	Association of Home Appliance Manufacturers
AHAM 1992	standard test cloth as specified in 1992 dryer test procedure published by AHAM in 1992
AHAM 2009	standard test cloth as specified in 2009 dryer test procedure published by AHAM in 2009
AHAM cloth	refers to both AHAM 1992 and AHAM 2009 test loads
BDW	bone dry weight
CEF	combined energy factor
CFM	cubic feet per minute
CFR	US Code of Federal Regulations
CI	confidence interval
cpt *or* cpct	compact size dryer
D1	test procedure detailed by DOE in Appendix D1 of 10 CFR 430 B
D2	informational test procedure detailed by DOE in Appendix D2 of 10 CFR 430 B
DOE	US Department of Energy (often used as shorthand to refer to standard test load as specified by the DOE dryer test procedure)
DP	dew point temperature
EC	electric compact
EC1	electric compact dryer model 1
EC2	electric compact dryer model 2
EF	energy factor [lbs_{BDW}/kWh]
ES	electric standard
ES1	electric standard dryer model 1
ES2	electric standard dryer model 2
g	gram
GS	gas standard
GS1	gas standard dryer model 1
L1-L2	voltage measured between two legs of split-phase power
L1-N	voltage measured between first leg of split-phase power and neutral
L2-N	voltage measured between second leg of split-phase power and neutral
lb	pound
ORNL	Oak Ridge National Laboratory
RH	relative humidity
RMC	remaining moisture content (unless noted, this refers to the final bulk RMC at end of test)
RMC_{bulk}	bulk RMC (i.e., average RMC for an entire load)
RMC_i	individual RMC of a single piece of cloth
$RMC_{i,max}$	maximum individual RMC among all cloths within a load
SMC	starting moisture content
T	temperature
TC	thermocouple
TP	test procedure
VAC	A/C voltage
ω	humidity ratio [lb_{water}/lb_{dryair}]

Abbreviations used in describing test cloths:

BX	boxer shorts (89 g in AHAM 1992)
HC	handkerchief (14 g AHAM 1992)

PC	pillow case (74 g in AHAM 1992; 219 g in AHAM 2009)
SH	sheet (775 g in AHAM 1992; 677 g in AHAM 2009)
ST	stuffer cloth (like a handkerchief) (17 g in DOE)
SR	long sleeve shirt (273 g in AHAM 1992)
TC	table cloth (314 g in AHAM 1992)
TS	t-shirt (138 g in AHAM 1992)
TW	towel (99 g hand towel in AHAM 2009; 99 g dish towel in DOE; 280 g bath towel in AHAM 1992)

EXECUTIVE SUMMARY

The US Department of Energy (DOE) test procedure for rating the energy performance of residential clothes dryers is defined in the *US Code of Federal Regulations, 10 CFR Part 430, Subpart B*. As of this writing, Appendix D is the mandatory test procedure, Appendix D1 becomes effective January 1, 2015, and Appendix D2 is provided for informational purposes and might become mandatory at a later date. The D and D1 test procedures evaluate dryers under manual termination by the test operator and include "field use" correction factors to adjust for differences between the test procedure and actual consumer use. The D2 test procedure is intended to directly measure dryer performance under automatic cycle termination.

In this study, high-quality data were acquired and documented to help inform stakeholders how dryer performance would be characterized under the D1 and D2 test procedures. This information might provide a better foundation for improving the performance of residential clothes dryers in the future.

The work investigated two standard size electric dryers, two compact size electric dryers, and one standard size gas dryer. All dryers use a tumble-type drum with forced air passed through the drum to dry clothes. All dryers are the vented type, where air is sourced from the conditioned, indoor space of the home and after circulating through the drum is exhausted through a duct to the outdoors.

Both the D1 and D2 test procedures use bulk remaining moisture content (RMC_{bulk}) as a performance metric. The DOE test load contains 39 individual pieces of clothing, the Association of Home Appliance Manufacturers (AHAM) 2009 test load contains 22, and the AHAM 1992 test load contains 16. In this study some effort was expended to examine the RMC of individual pieces of clothing in the load (RMC_i). Only limited testing was conducted but insights from this data may suggest strategies for dryer performance improvement.

This work also included preliminary investigations of automated cycle termination concepts not currently used in commercially available residential clothes dryers. Comparison of RMC_{bulk} and RMC_i data suggested that perhaps once RMC_{bulk} reaches some threshold, what is needed is not so much additional drying but a homogenization of RMC_i among the items in the load. Although the preliminary concepts evaluated here did not demonstrate clear benefits over existing approaches this might be an avenue for improving dryer efficiency in the future.

1. INTRODUCTION

This report documents the results and conclusions from laboratory evaluations conducted at Oak Ridge National Laboratory (ORNL) to establish the baseline performance of off-the-shelf residential clothes dryers under two test procedures and the potential for improving dryer performance through modifications to moisture-sensing methods and controls.

The energy efficiency of a dryer while operating is measured as the energy factor, or EF. Determining EF under the US Department of Energy's (DOE's) current test procedure involves a test operator manually stopping the dryer as it reaches a desired range of dryness. As of this writing, DOE had released for informational purposes a test procedure based on automatic cycle termination, which measures the dryer performance under automatic termination.

In direct relation to the prospective automatic termination test procedure, two key questions addressed in this work are:

1. Would using automatic termination change the repeatability of test results from one identical test to another?

2. Can an improved strategy for sensing and/or control lead to more efficient dryer operation under automatic termination?

In addition, this work also addresses the following questions, which are not directly related to the prospective automatic termination test procedure:

1. What is the performance (and repeatability of performance) of clothes dryers when using test loads other than those specified in the DOE test procedure?

2. What is the effect of dryer temperature setting on performance?

The remainder of Sect. 1 provides more detail on the background of clothes dryer efficiency testing, the objectives and methodology for this work, and the terminology adopted to describe the settings typically available on clothes dryers while allowing the dryer models to remain anonymous.

In Sect. 2, data are shown to demonstrate the validity of the tests conducted in this work, according to the requirements of the DOE test procedures and additional requirements imposed on this work. Section 3 presents the effects of test procedure, load type, temperature setting, and model on dryer performance. Section 4 presents data on the repeatability of performance as functions of the variables investigated in Sect. 3. A new way of measuring the dryness of test loads is introduced with measured data in Sect. 5. The existing dryer controls are characterized and some test results for modified controls are presented in Sect. 6. Finally, conclusions are summarized in Sect. 7.

1.1 BACKGROUND ON DRYER TEST PROCEDURES

DOE requires residential clothes dryers to be tested for compliance with minimum energy efficiency standards, as defined by the EF. The EF incorporates the energy used in the active drying cycle. The current test procedure for measuring the EF of residential clothes dryers is defined in the *US Code of Federal Regulations, 10 CFR Part 430, Subpart B, Appendix D* (10 CFR 430 2013).

DOE published final rules on January 6, 2011, and August 14, 2013, that provided some amendments to the existing manual-termination test procedure in Appendix D; established a new energy efficiency metric, as defined by the combined energy factor (CEF), which incorporates the energy used in the active drying cycle (the EF) as well as standby and off mode power consumption; established a new manual-termination test procedure in Appendix D1, with a mandatory compliance date of January 1, 2015; and established a new automatic-termination test procedure in Appendix D2 for informational purposes (76 FR 972; 78 RF 49608).

Compared with Appendix D, Appendix D1 starts with clothes less wet, uses a larger load, and uses cooler water (60°F instead of 100°F) to wet the clothes. Appendix D is not discussed any further in this report.

The key difference between informational Appendix D2 and soon-to-be-mandatory Appendix D1 is more fundamental. Appendix D2 specifies that the dryer automatically terminate based on its own controls when placed in "normal" operational settings while Appendix D1 specifies that the dryer be manually stopped by an operator at a specific remaining moisture content (RMC).

An overview of the main steps in the new Appendix D1 (manually stopped) test procedure is as follows:

- A load of cloth is dried to a "bone dry" state, in which it should weigh 8.45 lb +/-1%. Small articles of clothing (such as washcloths) are specified for making fine adjustments to the weight.
- The load is wetted to 57.5% moisture content by weight.
- The load is placed in the dryer, with the dryer set to "timed dry" and the maximum temperature setting.
- The dryer is allowed to run until the test operator manually stops it and weighs the cloth.
- The cloth should be in the range of 2.5–5.0% RMC, or else the test must be redone. The dryer is not allowed to enter into a cooldown mode.

The main steps in the Appendix D2 test procedure are very similar, with the exception that the dryer is placed into an automatic (moisture-sensing) mode and allowed to run through its full cycle including cooldown. The operator does not interrupt the cycle at any point and weighs the load at the end to determine the final RMC. If this final RMC is above 2.0%, the test must be run again set to the highest dryness setting available.

A summary of the key differences between the various DOE test procedures is given in Table 1. The work presented in this report involved some minor deviations from the DOE test procedures so that the data would be more useful for achieving the objectives of this study. Section 1.4.1 discusses all deviations in detail.

Table 1. Summary of key test procedure differences among Appendixes D, D1, and D2

	Appendix D	Appendix D1 (mandatory January 1, 2015)	Appendix D2 (currently informational)
Starting moisture content	70+/-3.5%	57.5+/-3.5%[a]	57.5+/-0.33%
Final remaining moisture content required	2.5–5.0%		<2%
Test load size (bone dry weight)	7.00+/-0.07 lb	8.45+/-0.085 lb	
Wetting water temp	100+/-5°F	60+/-5°F	
Automatic termination	No		Yes, "normal" auto mode
Correction for final RMC	Yes, corrected EF = measured EF × ($\Delta RMC_{actual}/\Delta RMC_{ideal}$)[b]		No correction
Correction for field use	"Field use" correction factor[c] is 1.04 for automatic termination dryers; 1.18 for timed dryers		Integrated into test procedure, no correction
Dryness setting	N/A		"Normal" or "medium"
Temperature setting	High		High (if selectable independent of auto setting)
Cooldown mode	Not used		Included
Standby and off mode	Not included	Included in CEF	

[a]For D1 tests in this work, the D2 starting moisture content tolerance of +/-0.33% was used (see explanation in Sect. 1.4.1).

[b]The ΔRMC_{ideal} is the ideal difference in RMC between beginning of test and end of test. This is 0.535 for Appendix D1. The ΔRMC_{actual} is the actual measured difference in RMC between beginning of test and end of test.

[c]The field use correction factor is multiplied by the per-cycle energy consumption (it reduces EF) to achieve a more realistic estimate of energy consumption when operated by consumers. For D1 tests in this work, a field correction factor of 1.04 was applied to all dryers since they were all equipped with an automatic termination setting.

1.2 BACKGROUND ON DRYER MINIMUM ENERGY EFFICIENCY REQUIREMENTS

This work investigated two standard size electric dryers, two compact size electric dryers, and one standard size gas dryer (all were vented types, i.e., dryers that use indoor air as a source and exhaust warm and humid air through a duct to the outdoors). The minimum efficiency requirements (from *10 CFR 430, Subpart C, §430.32*) for these categories are given in Table 2.

Table 2. Minimum energy efficiency requirements (EF or CEF) for the residential clothes dryer types evaluated in this work

	May 14, 1994–December 31, 2014 *EF*	From January 1, 2015 *CEF*
Electric standard	3.01	3.73
Electric compact (240 V)	2.90	3.27 (vented)
Gas standard	2.67	3.30

1.3 OBJECTIVES

ORNL's objectives in this investigation were to determine the baseline performance of several dryers, determine the test-to-test performance variability, characterize the existing automatic termination controls, and investigate strategies to improve performance under automatic termination. The performance metrics included EF, RMC, and duration of the drying cycle. Baseline performance and variability in performance were evaluated for five unmodified dryer models (two standard size electric, two compact size electric, and one standard size gas) under two test procedures (D1 and D2), with three test loads (DOE, Association of Home Appliance Manufacturers [AHAM] 1992, and AHAM 2009), and with two temperature settings (high and reduced).

1.4 METHODOLOGY AND METRICS

1.4.1 Approach to Test Procedures

1.4.1.1 Appendix D2 Tests

Tests conducted in this work under Appendix D2 followed the test procedure exactly as written with two deliberate exceptions:

1. The on-cycle EF was used as the measure of energy efficiency instead of the on- and off-cycle CEF. This decision was made so that the data would be more useful for distinguishing the effects of alternate strategies for improving on-cycle performance, such as automatic termination vs. timed drying and improved sensing and controls for automatic termination. Under the assumption that inactive power consumption is unrelated to active cycle performance, including inactive power consumption in all cases would only have served to obfuscate relative differences in the effects of the variables of interest. Note that if off-cycle energy consumption were factored in, the resulting CEFs would be lower compared with the EF used here by as little as <1% and up to 5%, depending on the dryer tested (based on data in Chapter 5 of the technical support documentation for DOE's 2009 Direct Final Rule).

2. The Appendix D2 test procedure requires that tests with final RMCs greater than 2.0% be rerun at the highest available dryness setting. All D2 tests with the DOE load resulted in RMCs of less than 2.0%. However, with non-DOE loads, many dryer models had a final RMC greater than 2.0%. Two of these (EC1 and EC2) had their tests rerun at the highest dryness setting (including the multiple identical repeatability tests for EC1), but the other models (ES1, ES2, and GS1) were not rerun. Technically the D2 test procedure applies only to testing with DOE loads, so reruns were not required. However, the decision was made to rerun tests for two dryers in order to investigate the effect of running on extra dry. Also, note that tests run with reduced temperature settings were not rerun if the final RMC was more than 2.0%, since the objective was to compare normal automatic termination behavior between temperature settings.

1.4.1.2 Appendix D1 Tests

Regarding tests under Appendix D1, it is important to note two important computational procedures that affect the D1 EFs (as defined in Appendix D1 and carried out for D1 tests in this report): (1) a "field use correction factor" and (2) a "final RMC compensation." The field use correction factor is defined as a fixed factor multiplied by the per-cycle measured energy consumption and is intended to correct for the differences between the test procedure and consumers' actual use in the field. For dryers capable of automatic termination (such as the five dryers evaluated in this work), the field use correction factor is 1.04. In effect, the final RMC compensation adjusts the measured EF by a ratio of RMC differences,

$\Delta RMC_{actual}/\Delta RMC_{ideal}$, where ΔRMC_{actual} is the actual difference in RMC between the beginning and the end of the test and ΔRMC_{ideal} is defined as 53.5%. This corrects for variation in final RMC, which, in D1 tests, is test operator dependent (not dryer dependent). Except where noted and explained in Sect. 6.3, compensation for final RMC and the field use correction factor were both incorporated into the values of EF reported for D1 tests in this work, in accordance with Appendix D1.

Further, for the D1 tests, the D2 tolerance of +/-0.33% on starting moisture content (SMC) was used instead of the D1 tolerance of +/-3.5%. This decision was made to aid in comparisons between D1 and D2 data sets.

1.4.1.3 Test Load Types

The CFR stipulates the use of a specific test load (herein referred to as "DOE load"). Two additional loads were obtained and used in this work: the load specified in the 1992 AHAM test procedure HLD-1-1992 (herein referred to as "AHAM 1992 load") and the load specified in the 2009 AHAM test procedure HLD-1-2009 (herein referred to as "AHAM 2009 load"). Together the AHAM 1992 and AHAM 2009 loads are sometimes referred to in this report as the "AHAM loads."

The full specifications of the "parent" AHAM standards were used in relation to the procurement, preparation, and maintenance of the AHAM test loads (including preconditioning, maintenance of required age profiles, etc.). However, with regard to methods of test, the DOE test procedures (Appendixes D1 and D2) were used exclusively (with the deviations noted in the preceding paragraphs). That is, the DOE test procedures were used on both the DOE loads and the AHAM loads.

1.4.2 Measurement of BDW, RMC_{bulk}, and RMC_i

Measurements of the bone dry weight (BDW), SMC, RMC_{bulk}, and RMC_i were carried out using a manual weighing process on a benchtop scale (a Mettler Toledo PM30000-K was used for most tests; a Mettler Toledo SB32000 was used for some tests).

The method used to measure BDW was as written in the CFR procedure. The clothes were brought to a bone dry state by drying on timed dry and the highest temperature setting until successive 10 minute intervals of drying did not change the total load weight by greater than 1%.

The method used to measure RMC_{bulk} was also as written in the CFR procedure. At the end of a test, the entire load was weighed together on a scale.

The method used to measure RMC_i was as follows: after measuring the bulk BDW, each cloth was weighed individually and its BDW_i recorded. BDW_{bulk} was then measured again. Then, at the end of a test, after the final bulk weight was recorded, each cloth was weighed individually, and the bulk weight was taken again. Each cloth was marked with a unique identifier to enable this.

1.4.3 Real-Time RMC_{bulk} Measurements

In addition to the manually weighed bulk and individual RMCs, the whole dryer under test was placed on a 4 × 4 ft platform scale with high resolution and accuracy (Mettler Toledo Vertex 2158 floor scale with IND 780 terminal). This would not be necessary for standard tests, but was done to provide additional insights for this work. As a test load dries, the weight of the whole dryer drops (by about 4.7 lb over a full drying cycle). This is only a few percent of the total weight of the whole dryer, and therefore the scale can only determine real-time RMC_{bulk} during the drying cycle with modest accuracy–especially considering the nonstatic nature of the dryer while in operation and the necessity for power and instrumentation cables to extend between the suspended dryer and other nonsuspended objects.

The as-realized accuracy for real-time RMC_{bulk} was about +/-2% RMC for electric models. It was significantly better (+/-0.5%) for the gas dryer, which had a much less substantial electrical power cable attached (carrying 2-3 A at 120 VAC, compared to up to nearly 30 A at 240 VAC for the electric models).

The RMC_{bulk} measured at the end of a test was much more accurate than the real-time value, and exceeded the accuracy required by the test procedure.

1.5 DRYER SETTINGS

Terminology to describe cycle settings differs among manufacturers. To make meaningful comparisons, the generic terminology described in Table 3 is used in this report.

Table 3. Generic terminology used in this report to describe dryer settings

	Generic terminology used in this report	**Example equivalent terms used by manufacturers**
Temperature	High	High, Normal, Cottons
	Reduced	Medium, Gentle, Easy Care, Permanent Press
Dryness	Normal	Normal, Optimum Dry, Cottons
	Extra dry	(highest dryness setting provided, according to Appendix D2)
Termination type	D2 *or* automatic	Normal cycle, Cottons cycle
	D1 *or* timed dry	Terminated manually by operator. The dryer was placed in Time Dry, Timed Dry, or XX Minutes mode, and was not allowed to enter cooldown before being manually terminated.
	N/A – not investigated	Time Dry (with cooldown), Timed Dry (with cooldown), XX Minutes (with cooldown)

2. TEST VALIDITY

Tests in this work were conducted according to the conditions specified in *10 CFR 430, Subpart B, Appendix D2*. This test procedure specifies the conditions given in Table 4. As previously explained, the D1 tests were conducted using the SMC value of 57.5% but with the D2 tolerance of +/-0.33%. All of the other test conditions in Table 4 are identical in Appendixes D1 and D2 and hence for the D1 and D2 data reported here. In addition, the uncertainty specifications of instrumentation used in this work are shown in Table 5.

The tests conducted were generally well within the requirements. For all tests declared valid, supporting information is shown in Fig. 1 through Fig. 4.

In Fig. 1, the line-to-line voltage (240 VAC) for each test was well within the required range of +/-1%. One dryer model (in tests 31 to 37 on EC2) tended to draw much more current from one power phase than the other, leading to one leg's voltage being a little high and the other being a little low. The line-to-line voltage stayed well within the required range (and the line-to-neutral voltages deviated only slightly beyond +/-1%). Note that tests 45–51 were on the gas dryer (GS1), which uses single-phase 120 VAC.

Table 4. Equipment and test conditions met or exceeded in this work as required by Appendix D2

	D2 Specification	Specification met or exceeded with	Supporting data
Voltage at dryer terminal block	240 VAC +/- 1%	Split-phase, electronically actuated, motorized variac (two-ganged on single shaft) with closed-loop control; typical response time 2 seconds	Fig. 1
Dryer exhaust restriction	AHAM exhaust simulator described in Sect. 3.3.5.1 of AHAM-HLD-1-2009	Sheet metal restrictor constructed according to AHAM specifications	N/A
Temperature of test room	75 +/- 3°F	Environmental chamber (+/- 1°F achieved for most tests)	Fig. 2
Relative humidity of test room	50 +/- 10%	Environmental chamber (+/- 2% achieved for most tests)	Fig. 2
Starting moisture content of test load	57.5 +/- 0.33%	Standard washing machine and supplemental spin extractors; Mettler Toledo PM30000-K or Mettler Toledo SB32000	Fig. 3
Bone-dry weight of test load	8.45 +/- 0.085 lb	Mettler Toledo PM30000-K or Mettler Toledo SB32000	Fig. 4

Table 5. Instrumentation used in this work

Measurement	Instrument	Accuracy
Temperatures	T-type thermocouples	+/-1°F
Relative humidity of room	Vaisala HMD60Y	+/-2.0% RH at testing conditions
Relative humidity of dryer exhaust	Vaisala HMT337 for high humidity, range 0-100% (warmed probe)	+/-2.7% RH or better under all conditions encountered
Weight of test loads and individual cloths	Mettler Toledo PM30000-K or Mettler Toledo SB32000	+/-0.3 g linearity; 0.1 g resolution +/-0.5 g linearity; 1 g resolution
Real time weight of whole dryer	Mettler Toledo Vertex 2158 floor scale (1,000 lb capacity) with IND 780 terminal	0.01 lb (4.5 g) resolution
Power consumption	Ohio Semitronics GW5-004C (wired for split-phase) with model 12974 current transducers	Power: 0.4% of measured value typical under testing conditions. Cumulative dryer cycle energy: 0.4% typical.
Voltage transducer (240 VAC)	Ohio Semitronics MVT-300A	+/-0.75 VAC (0.31% measured value)
Voltage transducers (120 VAC)	Ohio Semitronics MVT-150A	+/-0.38 VAC (0.31% measured value)
Natural gas flow rate	Elster American AC-250, temperature compensated, with ¼ ft^3 dial, RIO Tronics 10 pulse/rev pulser and digital totalizing counter	<1% (with 0.025 ft^3 resolution)
Natural gas calorific value	Union Instruments CWD 2005	+/-1.1% of measured value
Water hardness	Hach Model 5B Hardness Test Kit	~20 ppm
Data acquisition sample rate (all channels)	National Instruments cRIO	1 second

The ambient temperature and relative humidity for all baseline tests are shown in Fig. 2. These were both maintained in a far narrower range than required.

In Fig. 3, the measured SMC is shown to be maintained well within the tolerance. In practice this was not difficult, as the load would be spun to an SMC slightly lower than the target and then water would be spritzed onto the cloths to reach the exact target weight. The spritzing was conducted in such a way as to distribute the added moisture as uniformly as practical to the various items in the load.

The BDW for each test is shown in Fig. 4. Regarding the tests with compact loads that are too light, a mistake was made that resulted in the AHAM 2009 compact load being slightly underweight, at about 1.7% below 3.00 lb, compared with the specification of +/-1%. Because of schedule constraints it was decided to continue without rerunning those tests.

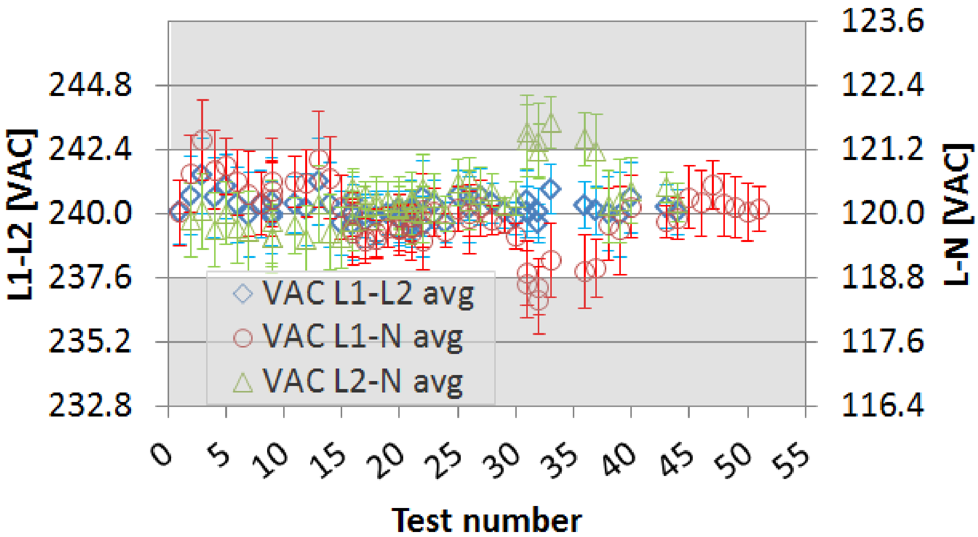

Fig. 1. Average and standard deviation (error bars) split-phase voltages at dryer terminal blocks during each test.

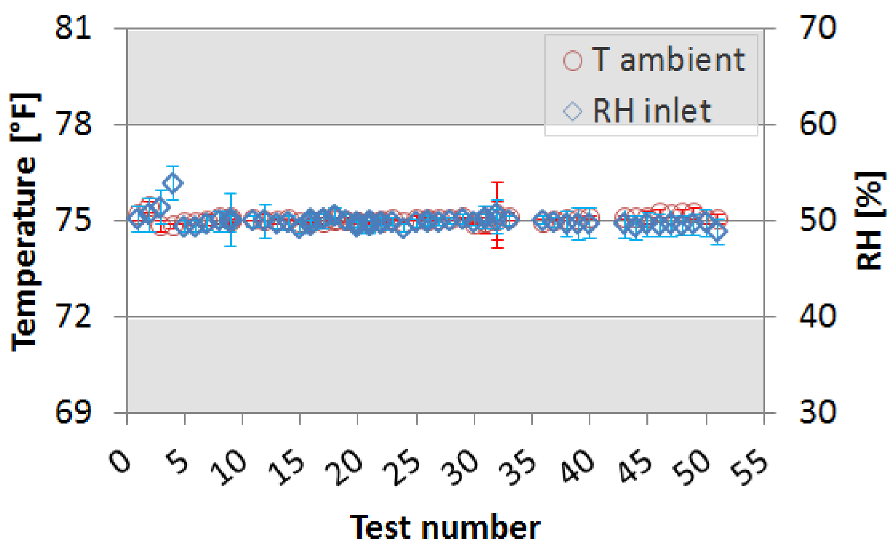

Fig. 2. Average and standard deviation (error bars) of environmental chamber temperature and relative humidity during each test.

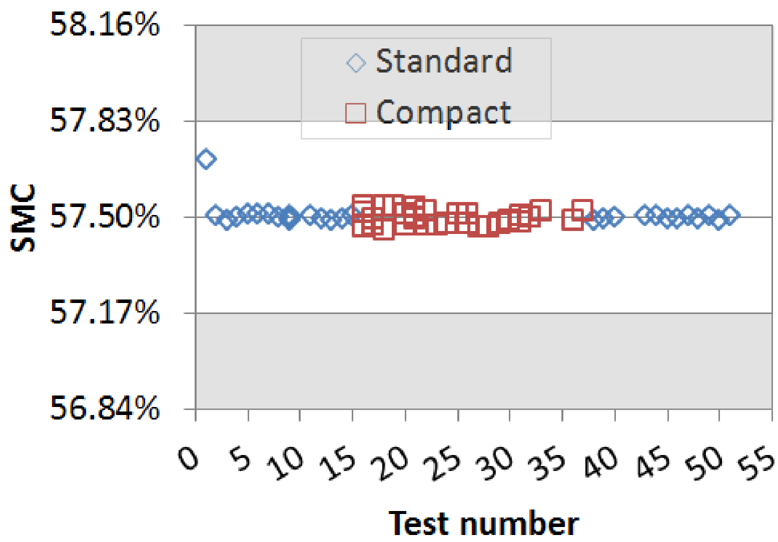

Fig. 3. Starting moisture content for each test.

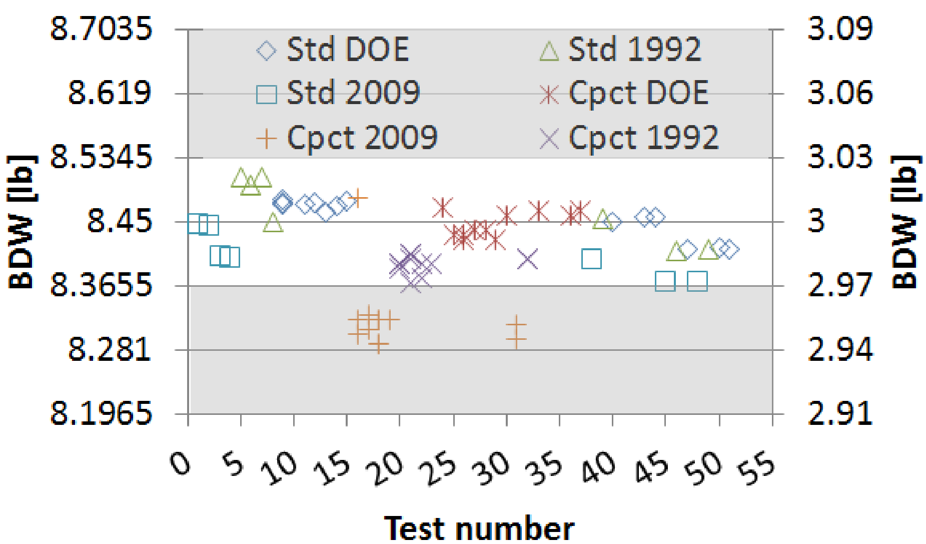

Fig. 4. Bone dry weight for each test.

3. EFFECT OF INVESTIGATED VARIABLES ON BASELINE DRYER PERFORMANCE

A test matrix was devised to effectively evaluate the performance of off-the-shelf dryers under various conditions, as shown in Table 6, and with key results shown in Table 7.

Table 6. Test matrix for baseline testing designed to allow independent evaluation of the effects of four variables of interest

Test number	Dryer	TP	Load	Setting - program	Setting - temp	Setting - dryness
1,2,3	ES1	D2	2009 AHAM	normal	high	normal
4	ES1	D2	2009 AHAM	normal	reduced	normal
5,6,7	ES1	D2	1992 AHAM	normal	high	normal
8	ES1	D2	1992 AHAM	normal	reduced	normal
9,10,11	ES1	D2	DOE	normal	high	normal
12	ES1	D2	DOE	normal	reduced	normal
13,14,15	ES1	D1	DOE	time dry	high	N/A
16,17,18,16e,17e,18e	EC1	D2	2009 AHAM	normal	high	nm, ex
19	EC1	D2	2009 AHAM	normal	reduced	normal
20,21,22,20e,21e,22e	EC1	D2	1992 AHAM	normal	high	nm, ex
23	EC1	D2	1992 AHAM	normal	reduced	normal
24,25,26	EC1	D2	DOE	normal	high	normal
27	EC1	D2	DOE	normal	reduced	normal
28,29,30	EC1	D1	DOE	time dry	high	N/A
31, 31e	EC2	D2	2009 AHAM	normal	no options	nm, ex
32, 32e	EC2	D2	1992 AHAM	normal	no options	nm, ex
33	EC2	D2	DOE	normal	no options	normal
34	EC2	D2	2009 AHAM	normal	reduced	normal
35	EC2	D2	1992 AHAM	normal	reduced	normal
36	EC2	D2	DOE	normal	reduced	normal
37	EC2	D1	DOE	normal	no options	N/A
38	ES2	D2	2009 AHAM	normal	reduced	normal
39	ES2	D2	1992 AHAM	normal	reduced	normal
40	ES2	D2	DOE	normal	reduced	normal
41	ES2	D2	2009 AHAM	normal	reduced	normal
42	ES2	D2	1992 AHAM	normal	reduced	normal
43	ES2	D1	DOE	time dry	reduced	N/A
44	ES2	D1	DOE	time dry	high	N/A
45	GS1	D2	2009 AHAM	normal	high	normal
46	GS1	D2	1992 AHAM	normal	high	normal
47	GS1	D2	DOE	normal	high	normal
48	GS1	D2	2009 AHAM	normal	reduced	normal
49	GS1	D2	1992 AHAM	normal	reduced	normal
50	GS1	D2	DOE	normal	reduced	normal
51	GS1	D1	DOE	time dry	high	N/A

Note: Blue denotes where additional tests were added to the original test matrix to accommodate the dryer's RMC performance. Green indicates a modification to accommodate the dryer's available settings. Purple indicates that a test's purpose was modified compared to the original test matrix. Gray indicates where tests were eliminated due to lack of available settings.

Table 7. Key results of baseline test matrix

Dryer model	TP	Load	Temp setting	Dryness setting	Test matrix designation	# tests	Duration [min] AVG	Duration SD (abs)	Duration SD (rel)	RMC_{bulk} [%] AVG	RMC_{bulk} SD (abs)	RMC_{bulk} SD (rel)	$RMC_{i,max}$ [%]	EF [lbs_{BDW}/kWh] AVG	EF SD (abs)	EF SD (rel)
ES1	D2	2009	High	Normal	1,2,3	3	42.97	1.50	3.5%	1.7%	0.1%	(NA)	-	3.18	0.08	2.5%
ES1	D2	2009	High	Normal	01R	1	40.17	-	-	1.7%	-	-	3.1%	3.03	-	-
ES1	D2	2009	Red.	Normal	4	1	39.48	-	-	2.5%	-	-	-	3.31	-	-
ES1	D2	1992	High	Normal	5,6,7	3	42.19	1.25	3.0%	3.8%	1.0%	(NA)	-	3.52	0.12	3.4%
ES1	D2	1992	High	Normal	05R	1	40.19	-	-	2.9%	-	-	7.8%	3.12	-	-
ES1	D2	1992	Red.	Normal	8	1	37.22	-	-	8.6%	-	-	-	4.01	-	-
ES1	D2	DOE	High	Normal	9,10,11	4	48.99	1.92	3.9%	0.8%	0.1%	(NA)	-	3.19	0.02	0.6%
ES1	D2	DOE	High	Normal	09R	1	44.78	-	-	1.1%	-	-	1.9%	2.98	-	-
ES1	D2	DOE	Red.	Normal	12	1	46.46	-	-	0.9%	-	-	-	3.28	-	-
ES1	D1	DOE	High	(timed)	13,14,15	3	28.63	0.57	2.0%	3.7%	0.5%	(NA)	-	3.92	0.04	1.1%
ES1	D1	DOE	High	(timed)	13R	1	22.84	-	-	3.5%	-	-	9.6%	3.7 7	-	-
EC1	D2	2009	High	Normal	16,17,18	4	25.75	1.26	4.9%	3.3%	1.9%	(NA)	-	3.42	0.19	5.6%
EC1	D2	2009	High	Ex. dry	16e,17e,18e	3	32.97	1.41	4.3%	1.0%	0.3%	(NA)	-	2.82	0.09	3.2%
EC1	D2	2009	Red.	Normal	19	1	26.00	-	-	3.4%	-	-	-	3.41	-	-
EC1	D2	1992	High	Normal	20,21,22	5	26.20	2.17	8.3%	6.3%	2.1%	(NA)	-	3.52	0.27	7.7%
EC1	D2	1992	High	Ex. dry	20e,21e,22e	4	35.42	4.48	13%	2.1%	1.0%	(NA)	-	2.79	0.27	9.6%
EC1	D2	1992	Red.	Normal	23	1	26.00	-	-	7.0%	-	-	-	3.62	-	-
EC1	D2	DOE	High	Normal	24,25,26	3	25.34	0.57	2.3%	1.1%	0.2%	(NA)	-	3.51	0.11	3.2%
EC1	D2	DOE	Red.	Normal	27	1	25.00	-	-	1.2%	-	-	-	3.57	-	-
EC1	D1	DOE	High	(timed)	28,29,30	3	18.62	0.53	2.9%	4.2%	0.8%	(NA)	-	3.76	0.08	2.0%
EC2	D2	2009	High	Normal	31	1	48.00	-	-	2.2%	-	-	-	2.65	-	-
EC2	D2	2009	High	Ex. dry	31e	1	57.46	-	-	1.0%	-	-	-	2.21	-	-
EC2	D2	1992	High	Normal	32	1	45.31	-	-	3.6%	-	-	-	2.94	-	-
EC2	D2	1992	High	Ex. dry	32e	1	53.97	-	-	1.4%	-	-	-	2.41	-	-
EC2	D2	DOE	High	Normal	33	1	42.54	-	-	1.2%	-	-	-	3.14	-	-
EC2	D1	DOE	High	(timed)	37	1	26.52	-	-	4.4%	-	-	-	3.73	-	-
ES2	D2	2009	Red.	Normal	38	1	43.88	-	-	0.8%	-	-	-	2.96	-	-
ES2	D2	1992	Red.	Normal	39	1	39.02	-	-	1.6%	-	-	-	3.15	-	-
ES2	D2	DOE	Red.	Normal	40	1	39.40	-	-	0.1%	-	-	-	3.19	-	-
ES2	D1	DOE	Red.	(timed)	43	1	23.33	-	-	4.4%	-	-	-	3.71	-	-
ES2	D1	DOE	High	(timed)	44	1	22.90	-	-	4.4%	-	-	-	3.78	-	-
GS1	D2	2009	High	Normal	45	1	50.64	-	-	1.6%	-	-	-	2.64	-	-
GS1	D2	1992	High	Normal	46	1	46.27	-	-	3.8%	-	-	-	2.88	-	-
GS1	D2	DOE	High	Normal	47	1	48.35	-	-	1.0%	-	-	-	2.93	-	-
GS1	D2	2009	Red.	Normal	48	1	49.45	-	-	2.0%	-	-	-	2.89	-	-
GS1	D2	1992	Red.	Normal	49	1	46.31	-	-	2.3%	-	-	-	3.13	-	-
GS1	D2	DOE	Red.	Normal	50	1	42.06	-	-	0.8%	-	-	-	3.14	-	-
GS1	D1	DOE	High	(timed)	51	1	22.28	-	-	3.4%	-	-	-	3.74	-	-

Note: Orange indicates an invalid RMC for D2 tests (>2.0%) with a high temperature setting, non-DOE load, and normal dryness (underlined if set to extra dry). Blue indicates an invalid RMC for D2 tests with a reduced temperature setting. Tests designated with a name ending in "R" were repeated to measure RMC_i. Tests designated with a name ending in "e" were repeated on "extra dry," according to D2 for EC1 and EC2

The dryer models included two electric standard units (ES1 and ES2), two electric compact units (EC1 and EC2), and a gas standard unit (GS1). The baseline test matrix in Table 6 was designed to allow for numerous comparisons to show the effects of (1) test load type, (2) test procedure—timed dry (D1) or automatic termination (D2), (3) temperature setting, and (4) dryer model. Dryness setting was set at normal (or default) for all automatic termination (D2) tests. A subset of these tests was also used to establish the test-to-test variability in performance results. Key results are shown in Table 7. The following sections show graphical representations and discussion of the results shown in Table 7.

3.1 EFFECT OF TEST PROCEDURE (D2 VS. D1)

To show the effect of test procedure, Fig. 5 shows EF, RMC, and duration for all tests conducted under normal dryness and high temperature settings with DOE cloth. In other words, it compares test results under D1 (timed dry) with test results under D2 (automatic termination), with as many other variables as possible held constant to show the effect of the test procedure.

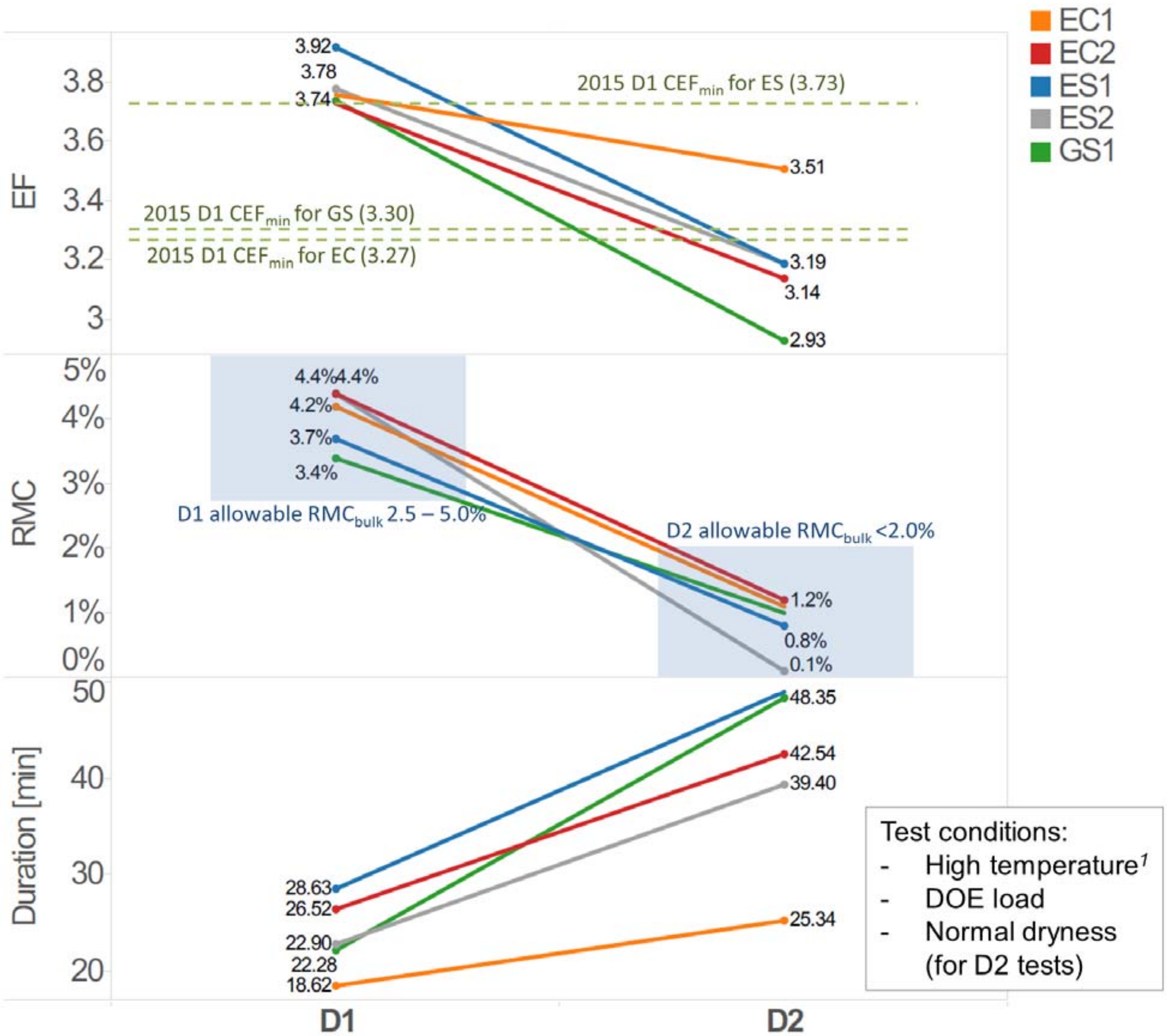

Fig. 5. Effect of test procedure (D2 vs. D1) on EF, RMC, and duration for each model (for tests with DOE load and high temperature[1]). Blue boxes show target RMCs for each test procedure. Green dotted lines show the minimum CEF standards effective in 2015 with D1 test procedure.

Compared with tests under D1, each dryer's EF dropped by 7 to 22% under D2. The drop in EF under automatic termination is only partly the result of the lower RMC requirement of Appendix D2. This

[1] The ES2 and EC2 units did not allow selection of temperature under automatic termination. Thus they are at the default temperature setting in this figure.

observation is based on the range in EF reduction being 7 to 22%, whereas the range in additional moisture removed was only 2.9 to 3.2%.

As the clothes get drier, the exhaust humidity decreases, the exhaust temperature rises, and apparently more energy is required for each additional percent reduction in RMC. Knowing this, one would expect the decrease in EF to be greater than the increase in moisture removal when slightly lowering the final RMC. However, it is instructive to examine recorded D1 tests in which the test operator "overshot" the target of 2.5–5.0%. For example, one D1 test on the GS1 dryer resulted in a final RMC of 0.1% (for this reason alone it was not a valid test under D1). The "EF" calculated without applying the field use correction factor or the final RMC compensation for this D1 test was 3.29, which is 11% *higher* than the D2 test result of 2.93 (which similarly does not have final RMC compensation or field use correction applied), even with a D1 final RMC 1.2% *lower* than the D2 test. From this it can be concluded that a significant amount of the additional energy consumption under D2 is from extended operation past the target final RMC.

3.2 EFFECT OF LOAD TYPE

To show the impact of different test cloths under the D2 test procedure, Fig. 6 shows EF, RMC, and duration for all tests conducted under normal dryness and high temperature settings using the D2 test procedure. Note that ES2 and EC2 did not have different temperature settings available under automatic termination and it would therefore be more precise to say they were run in their "default" temperature setting.

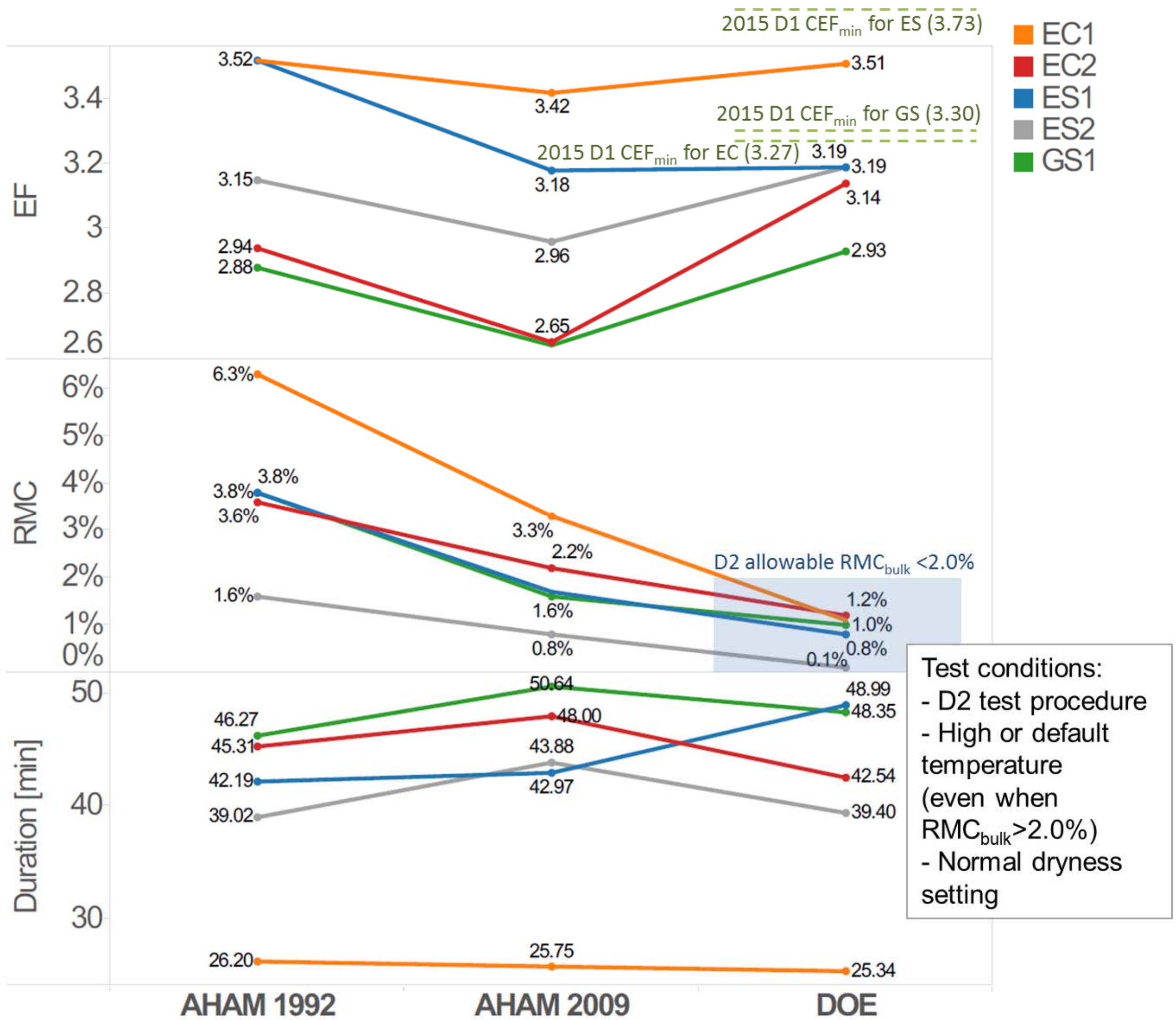

Fig. 6. Effect of test load on EF, RMC, and duration for each model (for tests with D2 test procedure, high-temperature setting). Blue box shows allowable RMC for DOE cloth. Green dotted lines (for reference) show minimum CEF standard effective 2015 for CEF evaluated under D1.

Evaluating the results for the D2 tests with the three different clothing loads, the following observations can be made:

- The RMC_{bulk} of each dryer's clothing load decreased from AHAM 1992 to AHAM 2009 and decreased again from AHAM 2009 to the DOE load.
- Among the three load types, each dryer's D2 EF was lowest with the AHAM 2009 load. Depending on the dryer, the EF may be highest with either the AHAM 1992 (also with high RMC_{bulk}) or the DOE load.
- In general each dryer's cycle duration did not vary much across the three loads.
- Comparing dryer models to each other, relative EF and RMC performance with the DOE load was a good predictor of relative performance with the other loads.

Many of the D2 tests in Fig. 6 with non-DOE loads resulted in final RMCs higher than 2.0%. According to the D2 test procedure (which technically does not cover non-DOE loads), these tests would need to be rerun at the highest available dryness setting (generically referred to as extra dry). This was done for two dryer units (EC1 and EC2) for those D2 tests with non-DOE loads in which they did not reach <2.0% RMC. These results are shown in Fig. 7 compared to the performance with DOE loads at normal dryness setting.

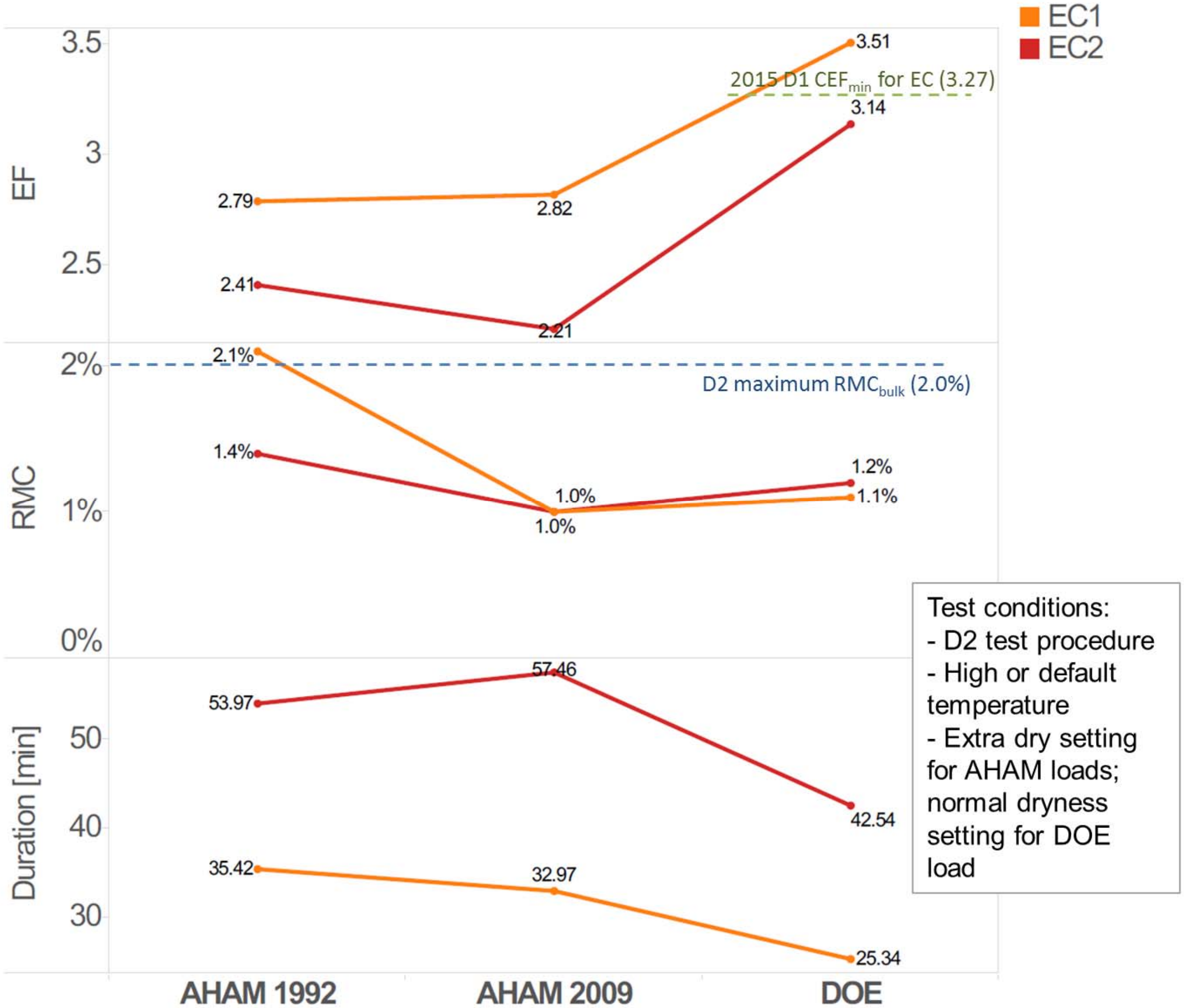

Fig. 7. Performance for EC1 and EC2 when running under the extra dry setting for AHAM 1992 and AHAM 2009 loads (normal dryness setting with DOE load).

3.3 EFFECT OF DRYNESS SETTING

Based on the results discussed in Sect. 3.2, it is also possible to plot the effect of the extra dry setting for EC1 and EC2 with the AHAM loads. This is shown in Fig. 8. Note that the 2015 minimum CEFs would not actually apply to these results since the CEF applies only to the DOE load. For both dryers, the effect of the extra dry setting was to decrease EF, decrease RMC, and increase duration compared with the normal dryness setting.

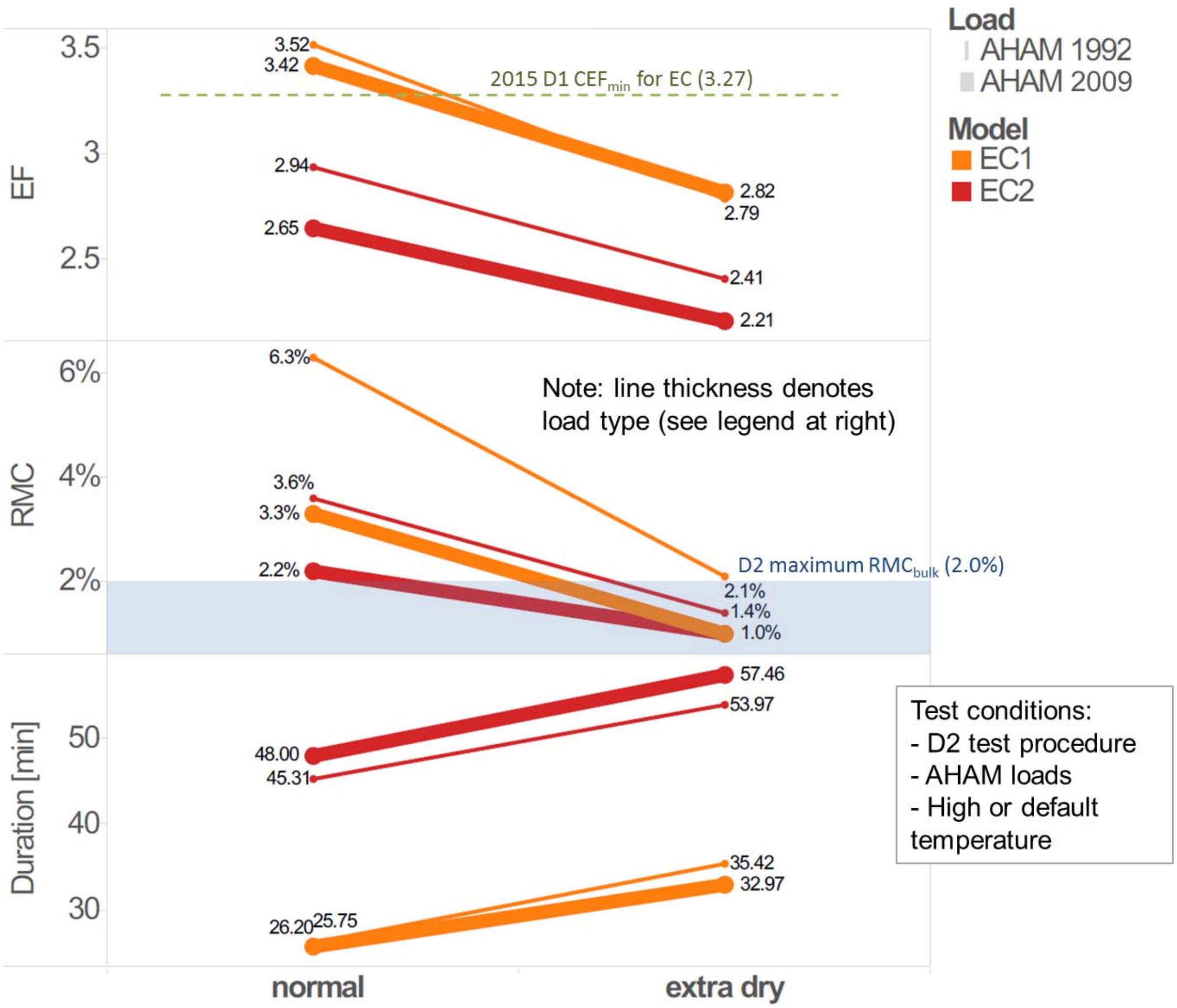

Fig. 8. Effect of dryness setting.

3.4 EFFECT OF TEMPERATURE SETTING

Nomenclature for temperature settings differs among manufacturers. In this report, the term "reduced" refers generically to a temperature setting that is one level below the highest level provided (not including extremes that may be provided by some manufacturers such as "antibacterial"). This reduced setting may be called "Medium," "Easy Care," "Permanent Press," or "Gentle." Also, temperature settings may be referred to by manufacturers as "temperature" or "heat." The highest temperature level provided is typically the default setting, and may be called "High" or "Normal."

The effect of the temperature setting (under D2 automatic termination) on EF, RMC, and duration is shown for three different loads and three dryer models in Fig. 9. Results for the EC2 model were not included because there was no available reduced temperature setting. Results for the ES2 model were not included because the "high" setting could not be selected under automatic termination. In this figure, line thickness indicates load type and line color indicates dryer model.

The reduced temperature setting tends to slightly increase EF, slightly increase the final RMC_{bulk}, and counterintuitively slightly decrease the cycle duration. An explanation for the duration increase seems to be related to a lower peak temperature of the cycle under the reduced setting. The energy used in the first ~30 minutes was similar for reduced and high temperature settings. Under the high temperature setting the exhaust subsequently reached a higher peak temperature before the onset of cooldown, leading to longer cycle duration under high temperature setting.

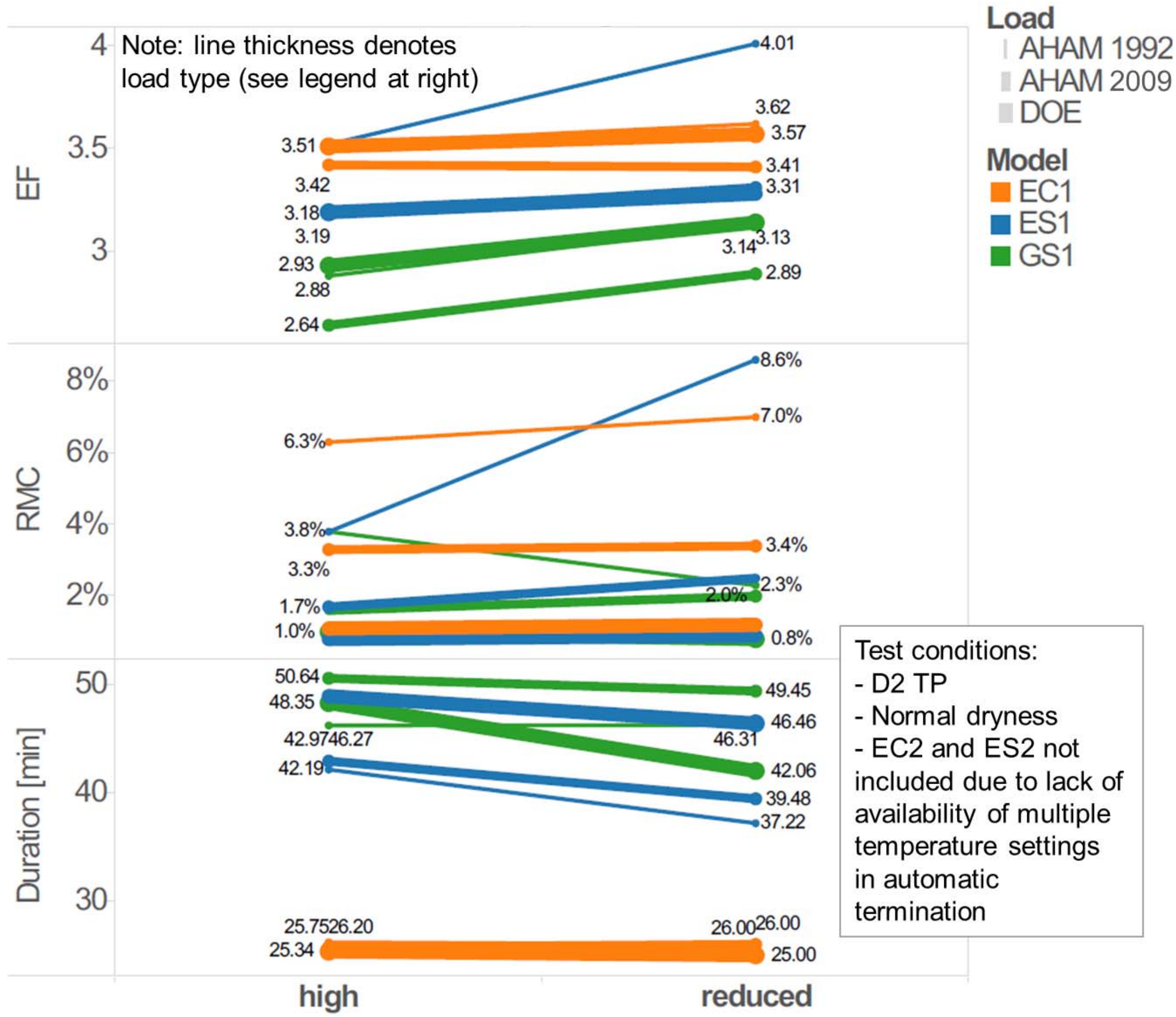

Fig. 9. Effect of temperature setting on EF, RMC, and duration for each model and load type for tests with D2 test procedure.

For one dryer, the effect of a reduced temperature setting was also evaluated under the D1 test procedure, as shown in Fig. 10. Reduced temperature had no significant effect on EF, RMC_{bulk} or duration for D1 tests.

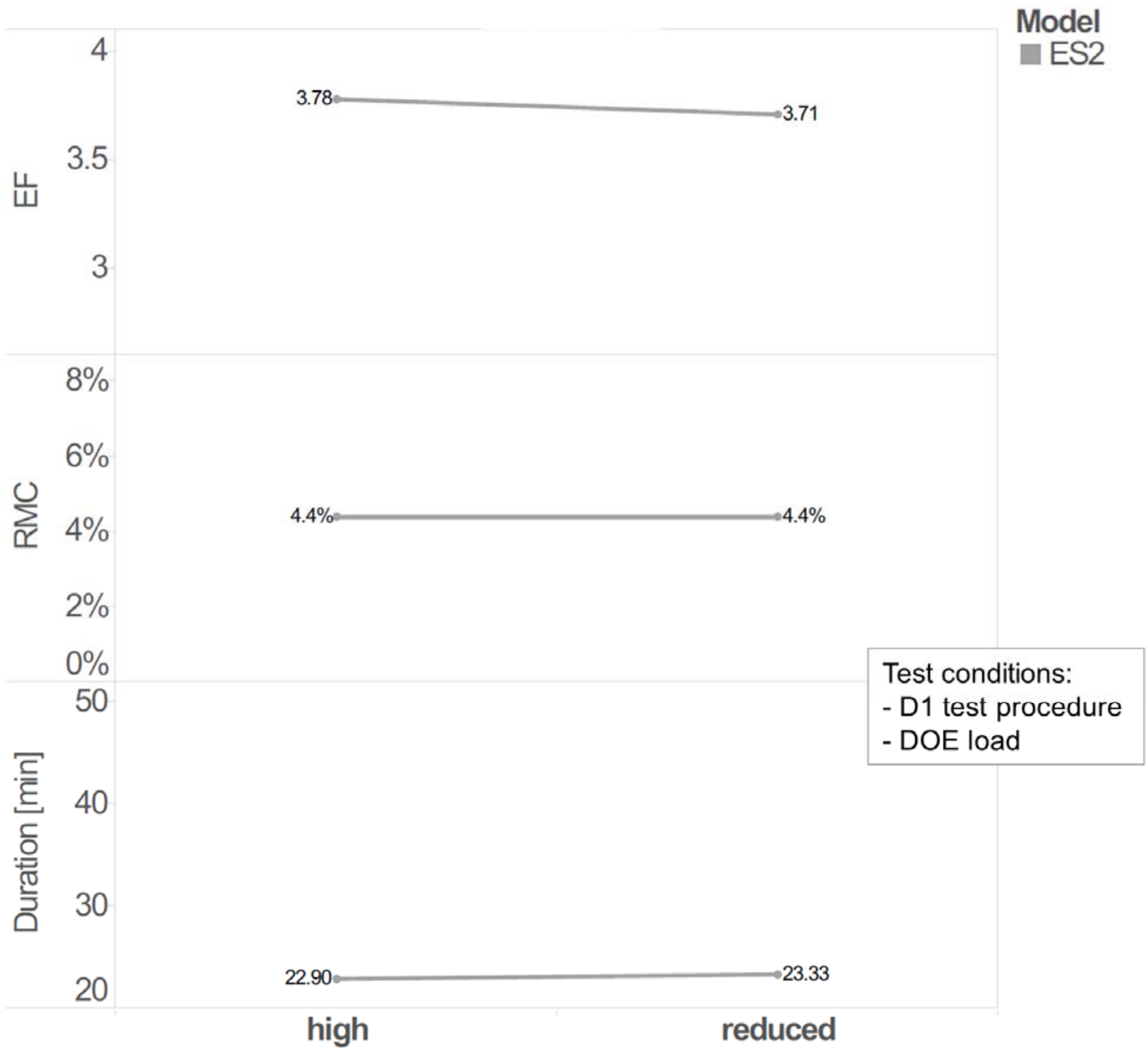

Fig. 10. Effect of temperature setting under the D1 test procedure for ES2.

3.5 EFFECT OF DRYER MODEL

The significance of the effect of the dryer model is shown in Fig. 11, which details the EF, RMC, and duration for each test load. All results in Fig. 11 are for D2 tests with normal dryness and high-temperature settings.

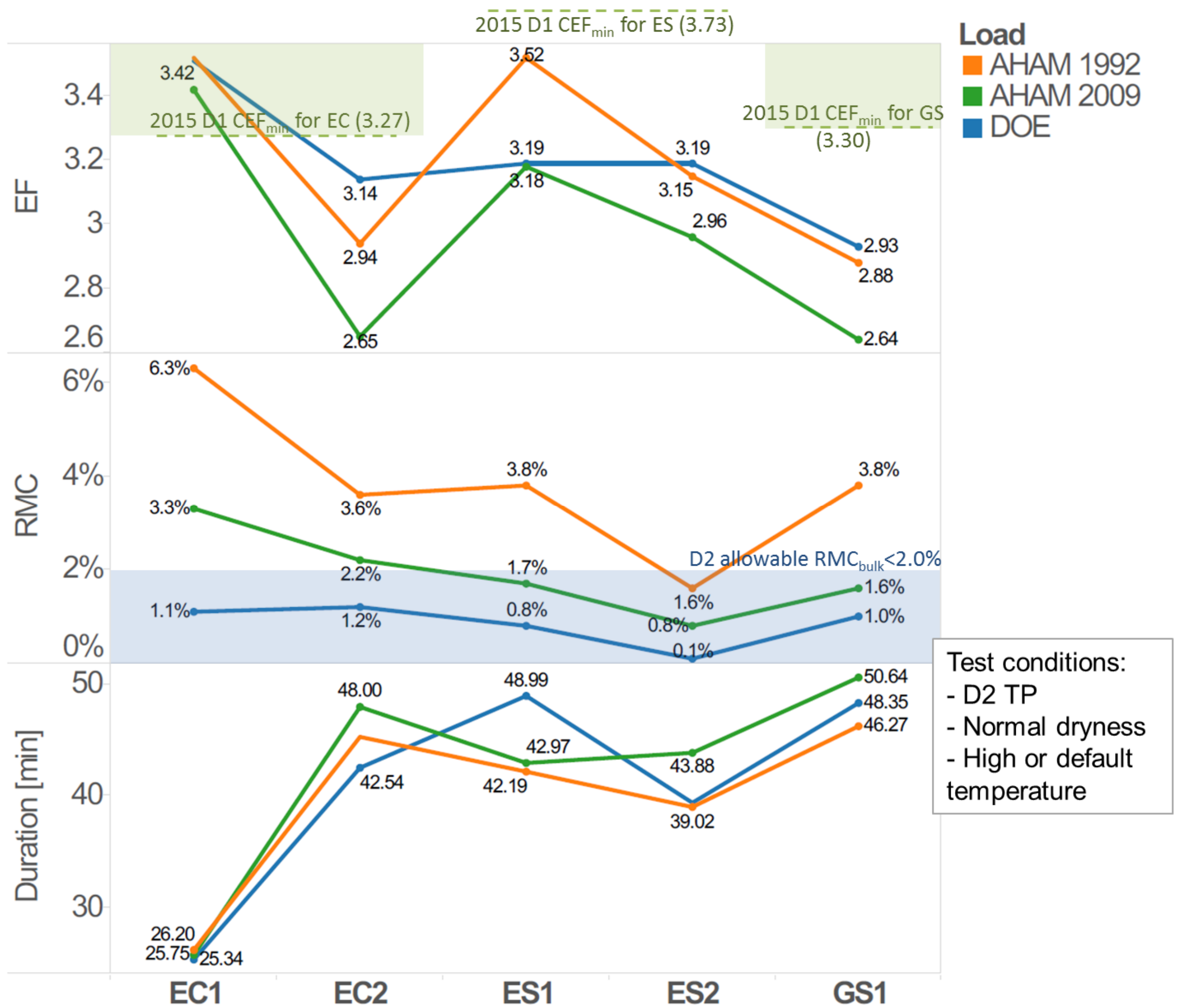

Fig. 11. Effects of dryer model on EF, RMC, and duration for each test load (for tests with D2 test procedure and high or default temperature setting). Note that the 2015 CEF standards are applicable to the DOE load.

Observations from Fig. 11 include the following:

- EF
  - Only one dryer (EC1) had an EF exceeding the 2015 CEF requirement (relevant to D1), under the D2 test procedure. This dryer also had an acceptable D2 RMC_{bulk} (1.1%) with DOE cloth but had a significantly higher RMC_{bulk} for AHAM 2009 (3.3%) and AHAM 1992 (6.3%).
  - EC2, ES2, and GS1 performed best with the DOE load and worst with the AHAM 2009.
  - The EF achieved by EC1 was relatively insensitive to test load. This was in part because it had the widest variation in RMC_{bulk} among the five models.
  - The ES1 dryer performed best with AHAM 1992, where it also had the shortest duration (with a relatively high RMC_{bulk} of 3.8%).
- RMC
  - All dryers met the <2.0% RMC_{bulk} requirement for D2 tests with DOE cloth. Three met it with the AHAM 2009, and only one met it with AHAM 1992 cloth.

- All dryers had their respective lowest RMC_{bulk} with the DOE load.
- All dryers had their respective highest RMC_{bulk} with an AHAM 1992 load, with wide variation in this RMC_{bulk}, from less than 1.6 to 6.3%.
- The RMC_{bulk} with AHAM 2009 ranged from 0.8 to 3.3%.

- Duration
  - The EC1 had dramatically shorter duration than the standard models, while the EC2 had slightly longer than average duration when compared with standard models.
  - The EC1 barely changed its duration across different loads, resulting in wide variations in RMC. As shown later, it had high test-to-test variability in EF and RMC in identical tests.

4. REPEATABILITY OF RESULTS

The results in this section are presented mainly as standard deviations (population type). Note that for a conventional uncertainty with 95% confidence interval, two standard deviations are required. Standard deviations were calculated based on results from multiple (at least three) identical tests. These tests were conducted on two dryer models only (ES1 and EC1).

All test results that had repeats are shown in Fig. 12. They fall into ten test categories as defined by dryer model, load, and dryness setting. Most have three repeats per category, two categories have four repeats, and one has five repeats. All tests conducted for repeatability used the high temperature setting.

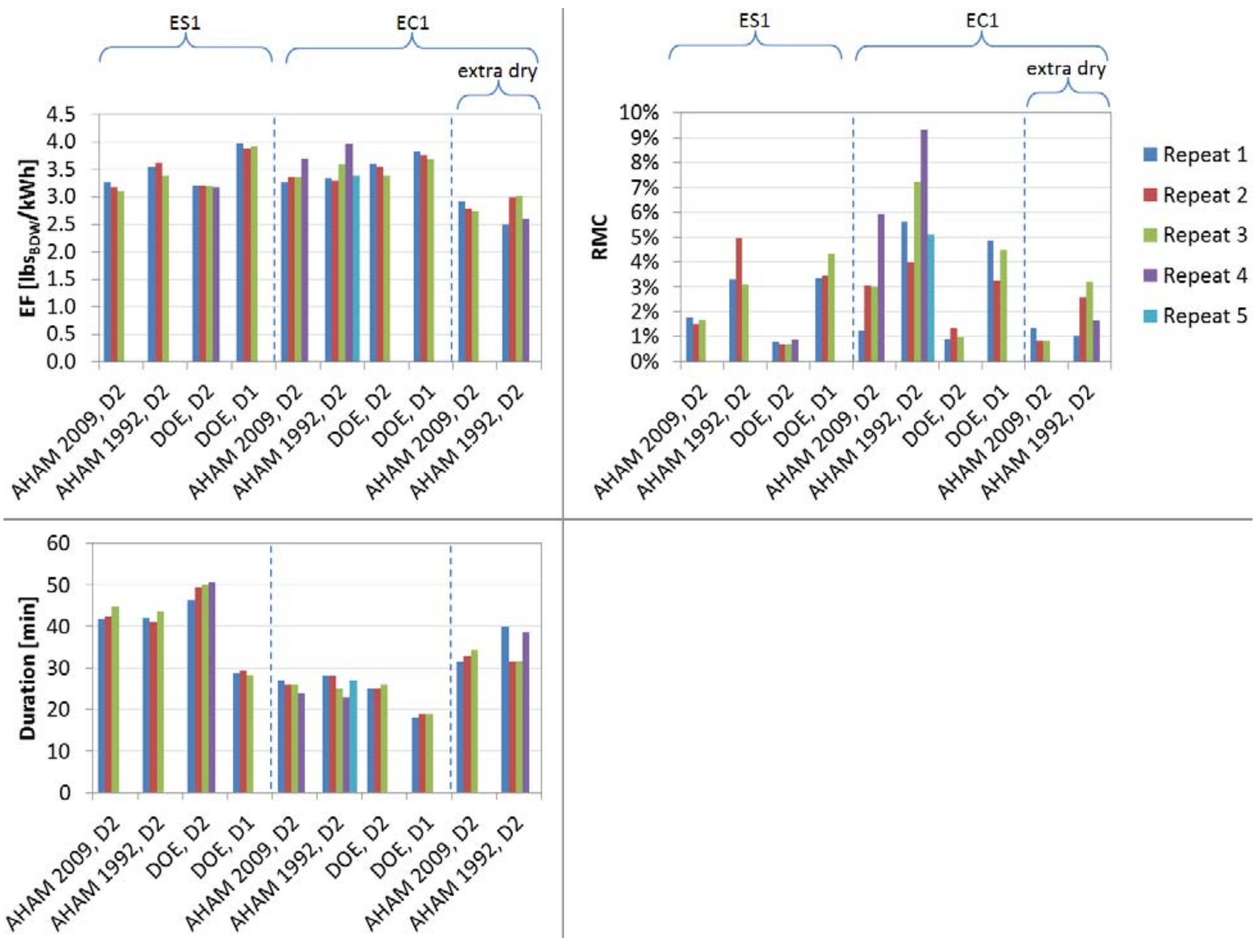

Fig. 12. Performance results for repeated tests.

Perhaps the most important repeatability result is the effect of the test procedure on EF repeatability as shown in Fig. 13. For ES1, the repeatability under D2 was better (0.6% vs. 1.1%). For EC1, the repeatability under D2 was worse (3.2% vs. 2.0%). Note that the number of identical tests from which each standard deviation was calculated was three (except ES1 under D2, where the number was four). *Overall, the data here are inconclusive about whether repeatability of EF under D2 is higher or lower than repeatability of EF under D1.*

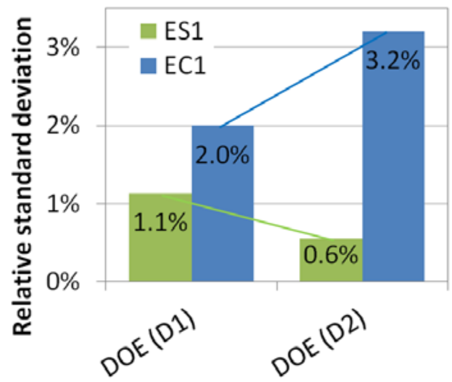

Fig. 13. Effect of test procedure on repeatability of EF for two dryer models with DOE load.

Fig. 14 shows the standard deviations in EF, RMC, and duration. It includes tests under the D1 test procedure with the DOE load and under the D2 test procedure with all load types. Note that RMC needs to be shown as absolute standard deviation (with units of %RMC) for meaningful results. Each bar represents the standard deviation for a set of identical tests (at least three identical tests in all cases and four or five in some).

Clearly dryer model and/or dryer size has a large influence on the degree of variability in results. The EC1 had consistently higher variability in EF and RMC with all load types, while having higher variability in duration for DOE and AHAM 2009 loads but lower variability with AHAM 1992 load.

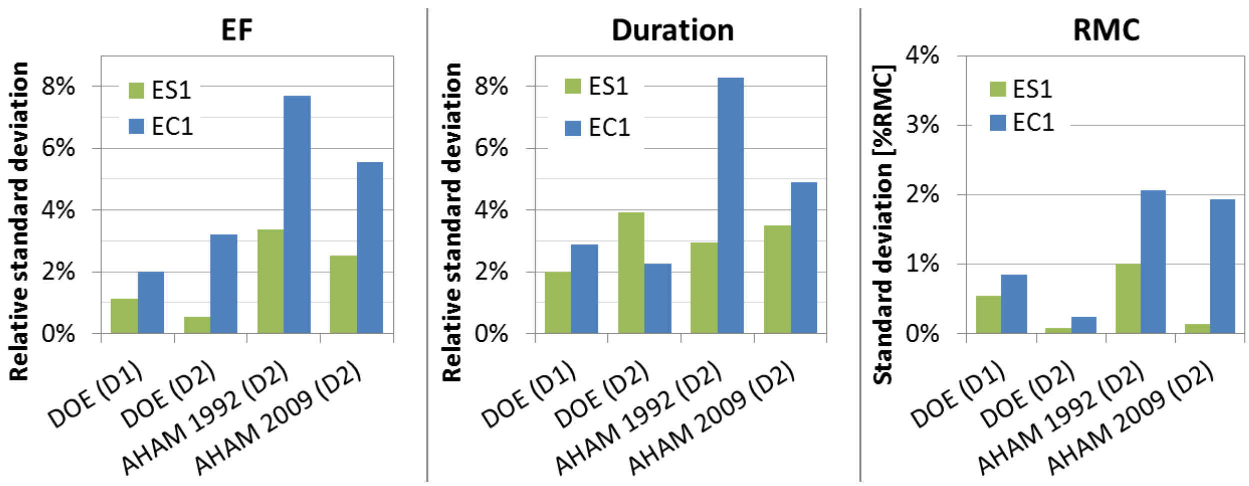

Fig. 14. Standard deviations of EF, duration, and RMC_{bulk} under various test procedures and loads.

When comparing D1 to D2, it is important to note that variability in duration and RMC are operator-dependent in D1 testing (the operator is allowed to stop the dryer with an RMC anywhere between 2.5 and 5.0%). It is important to note that the EF is much less operator dependent than RMC or duration, since D1 uses final RMC compensation in the calculation of EF.

Comparing the D2 tests to each other, the DOE cloth usually resulted in the lowest variability for EF, duration, and RMC for both dryer models. The single exception was variability of duration with ES1, which was similar among all three loads, but worst with the DOE load. For EC1, all performance metrics had the lowest standard deviation with the DOE load.

RMC variability under D2 test procedure with the DOE load was very low, with standard deviations of 0.1% for ES1 and 0.2% for EC1. The AHAM loads generally had considerably higher variability and may or may not be below 2.0% final RMC_{bulk}, depending on the test run. For example with the EC1 dryer, three tests out of four with AHAM 2009 had RMC higher than 2.0%. An additional set of tests was run on "extra dry" (according to the D2 test procedure). All repeats on "extra dry" were below 2.0%.

The AHAM 1992 load had the highest RMC variability, was as low as 4% and as high as >9% with normal dryness with the EC1. On "extra dry" with EC1, two repeats were <2.0% and two were between 2.5 and 3.2%.

Standard deviations of performance metrics can be compared under the two dryness settings for the EC1 dryer in Fig. 15. For EF and duration, the results were mixed, with variability increasing for the AHAM 1992 load and decreasing for the AHAM 2009 load. For RMC_{bulk}, the extra dry setting led to a significant decrease in variability for both load types.

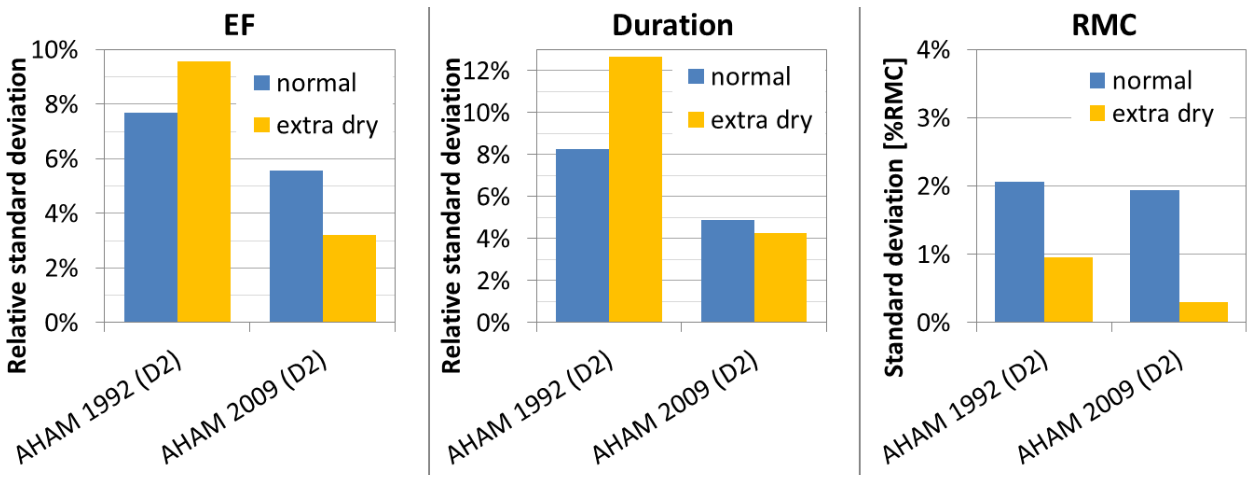

Fig. 15. Effect of dryness setting on variability: standard deviations of EF, duration and RMC_{bulk} for EC1 dryer with normal and extra dry settings, under D2 test procedure.

5. INDIVIDUAL RMC

5.1 INDIVIDUAL RMC OF BASELINE TESTS

In this work, a new term, “individual RMC” (RMC_i), was defined and measured. This metric is the RMC of a single item of cloth (for example a single towel or shirt) out of a test load that might be comprised of 16–39 individual items. While not directly related to D1 or D2 test procedures, the author believes that insights from RMC_i data might provide clues for how to design more energy efficient dryers.

Another metric, the “excess RMC_i score”, was also defined in order to help interpretation of results within this report and is explained later in this section.

Acquiring the individual RMC data requires that each item (39 pieces in the case of an 8.45 lb DOE load) be weighed at the BDW stage and again at the end of the test. In this work, bulk weights were taken two extra times as well: the bulk BDW was taken before and after individual BDWs were taken, and the bulk final weight was taken before and after the individual final weights were taken. This was done to verify that the bulk weight did not undergo a significant change during the time it took to measure each item individually. The additional technician time required to take these 78 individual weights plus two additional bulk weights was approximately 20 minutes per test (roughly 10 minutes at the bone dry stage and 10 minutes more after the end of the dry cycle).

In baseline testing, individual RMC was not recorded. After completion of baseline testing, four tests were rerun (referring to test matrix designations 1, 5, 9, and 13 in Table 6) to characterize the baseline distribution of RMC_i under D1 and D2 testing (high-temperature setting) for one dryer model (ES1).

The types of cloth found in each test load are summarized (along with their shorthand aliases) in Table 8. Also see Table A.1 in the Appendix for additional information about each test load.

Table 8. Items found in each test load

Test load	Test load item description	Item alias
DOE	towels	TW
	washcloths	ST
AHAM 1992	sheets	SH
	table cloths	TC
	bath towels	TW
	long sleeve shirts	SR
	T-shirts	TS
	pillowcases	PC
	boxer shorts	BX
	wash cloths	WC
	handkerchiefs	HC
AHAM 2009	sheets	SH
	pillowcases	PC
	towels	TW

To characterize the RMC_i distribution for baseline tests, the test matrix and key results shown in Table 9 and plotted in Fig. 16 were obtained. This included four repeats of tests from the baseline test matrix (as was shown in Table 6), plus two tests with double-size (16.9 lb) loads. One of these (test XL1) contained an 8.45 lb 1992 AHAM load plus an 8.45 lb 2009 AHAM load, and the other (test XL2) consisted of two 8.45 lb DOE loads.

Table 9. Test matrix and key results for characterizing RMC_i tests

Test name	Dryer	TP	Load	Temp. setting	Dryness setting	EF	Dur-ation [min]	RMC_{bulk}	$RMC_{i,max}$	Excess RMC_i score
1R	ES1	D2	2009 AHAM	high	normal	3.03	40.2	1.7%	3.1%	0
5R	ES1	D2	1992 AHAM	high	normal	3.52	40.2	2.9%	7.8%	7.3
9R	ES1	D2	DOE	high	normal	2.98	44.8	1.1%	1.9%	0
13R	ES1	D1	DOE	high	(timed)	3.77	22.8	3.5%	9.6%	16
XL1	ES1	D2	1992+2009	high	normal	3.94	54.3	5.8%	23%	26
XL2	ES1	D2	DOE+DOE	high	normal	3.51	63.8	0.4%	1.0%	0

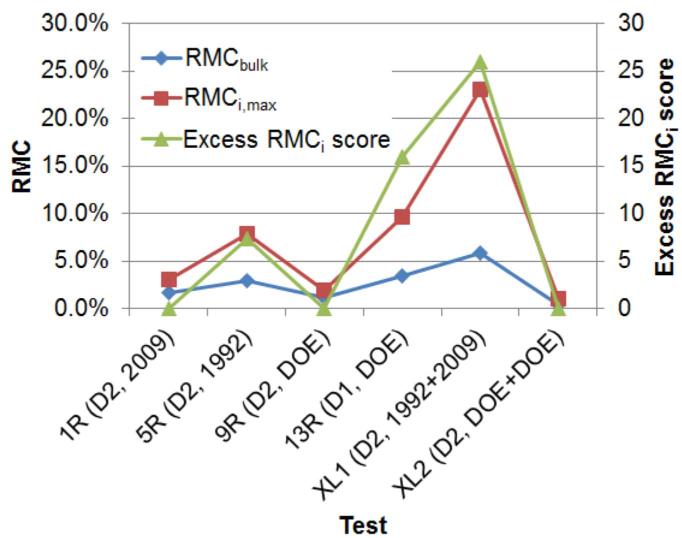

Fig. 16. Results of RMC_{bulk}, RMC_i, and excess RMC_i score for baseline and extra-large load tests.

Figures 17–19 show the distribution of individual RMCs measured for all three load types under D2 automatic termination. Fig. 20 shows the distribution of RMC_i for the DOE load under the timed dry D1 test procedure. Note that the average weight of each item type is shown in the legend of each figure (e.g., TW 99 g means the towels in that load had an average BDW of 99 g). Due to slight variations in BDW, the weight for an item type (e.g., TW or ST) may change slightly from one test to another. In addition, note that the individual RMC procedure was independent of the RMC_{bulk}; that is, the RMC_{bulk} was still determined in the conventional way by weighing the entire load together.

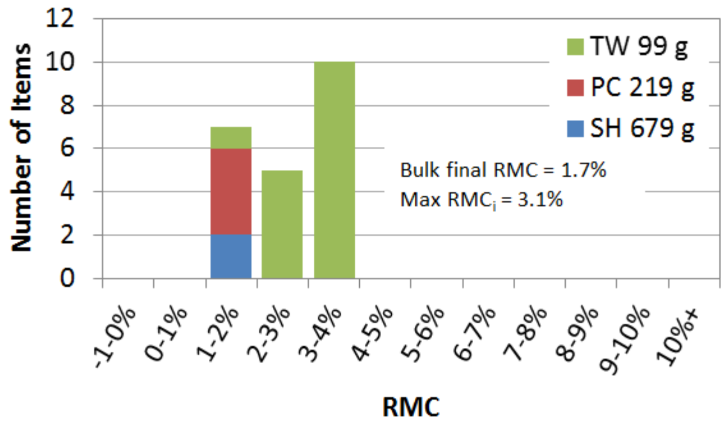

Fig. 17. AHAM 2009 in ES1 dryer at high temperature and normal dryness with automatic termination (D2 test procedure, rerun of Table 7 #1).

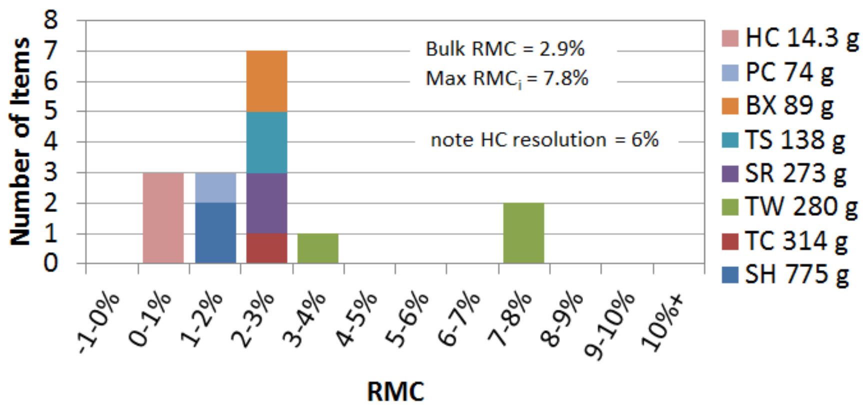

Fig. 18. AHAM 1992 in ES1 dryer at high heat and normal dryness with automatic termination (D2 test procedure, rerun of Table 7 #5).

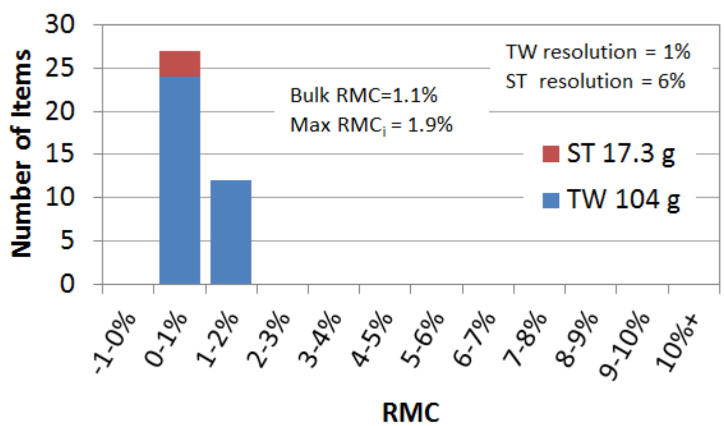

Fig. 19. DOE cloth in ES1 dryer at high heat and normal dryness with automatic termination (D2 test procedure, rerun of Table 7 #9).

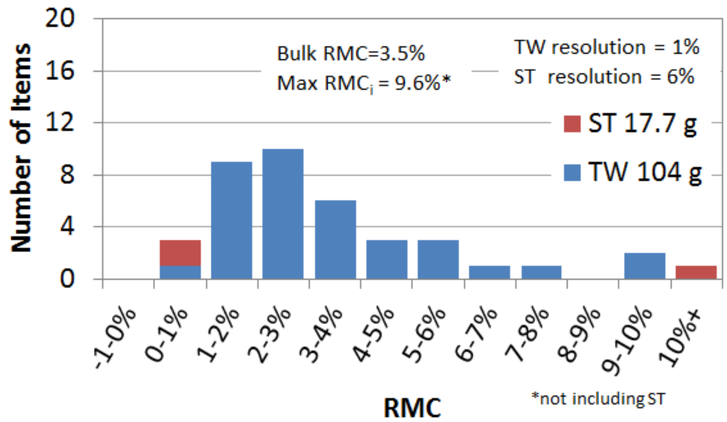

Fig. 20. DOE cloth in ES1 dryer at high heat with timed dry (D1 test procedure, rerun of Table 7 #13).

Under automatic termination with bulk RMC of <2.0%, the dryer generally dried all individual items to below 4% final RMC_i, with the only exception being two 280 g terry cloth towels in the AHAM 1992 load. These came out between 7–8% RMC, and a third identical towel in the same load came out below 4%.

Fig. 20 shows the RMC_i distribution with the DOE load under D1. This is not directly comparable to RMC_i distributions under D2. D1 addresses the difference collectively through the use of RMC compensation and the field use correction factor.

To provide a simple representation of the distribution of RMC_i, a novel "excess RMC_i" scoring method was used in this report. Note that under this method there is a multitude of possible distribution "shapes" that would result in a score of 0. The scoring method is not intended to fully capture the shape of the RMC_i distribution but rather to capture operation that might result in wet outlier items in spite of acceptable bulk dryness. The scoring method was as follows:

- Each item below 5% RMC was assigned a score of 0.
- Each item between 5–7% RMC was assigned a score of 1.
- Each item above 7% RMC was assigned a score of 3.
- The raw score for a test run was the sum of all individual scores.
- The DOE test load contained 39 items, the AHAM 2009 contained 22, and the AHAM 1992 contained 16 items. To account for this, the scores for non-DOE loads were normalized (e.g., an AHAM 2009 raw score would be multiplied by 39/22 to get a normalized score, comparable with a raw DOE score).

Under this excess RMC_i scoring methodology, the scores of the tests in Fig. 17 through Fig. 20 were 0, 7.3, 0, and 16, respectively, as shown in Table 9.

In addition, one test (designated XL1 in Table 9) was run with a double-sized load (an 8.45 lb AHAM 1992 load plus an 8.45 lb AHAM 2009 load). Its distributions of RMC_i under automatic termination and high temperature are shown in Fig. 21 (for the AHAM 2009 portion of the load) and Fig. 22 (for the AHAM 1992 portion of the load). Interestingly, the AHAM 2009 portion of the load had higher load-type-averaged RMC and much higher $RMC_{i,max}$ than the AHAM 1992 portion of the load, which is the reverse of the results when each load was used on its own. The excess RMC_i score for this test was 26.7.

An oversized load using DOE cloth was also run, using two 8.45 lb DOE test loads. Its distribution of RMC_i under automatic termination with high temperature is shown in Fig. 23. Here, the distribution of the double-sized load was not substantially different from the single 8.45 lb DOE load under automatic termination.

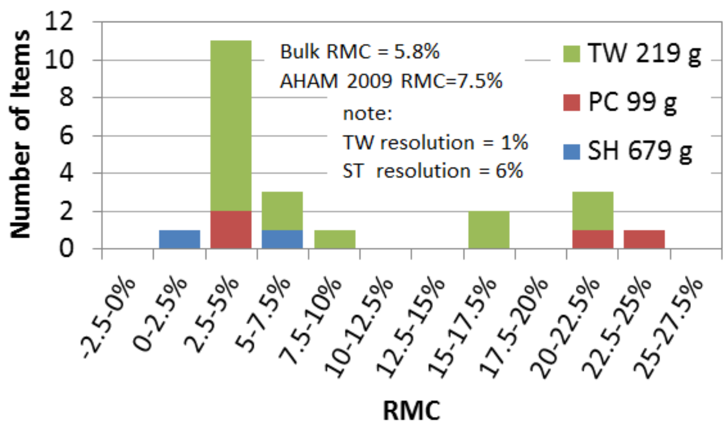

Fig. 21. RMC_i for the AHAM 2009 half of the double-sized load.

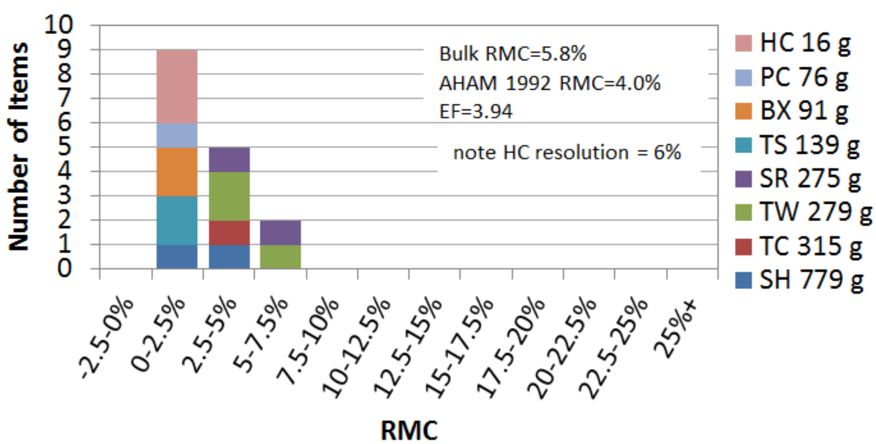

Fig. 22. RMC_i for the AHAM 1992 half of the double-sized load.

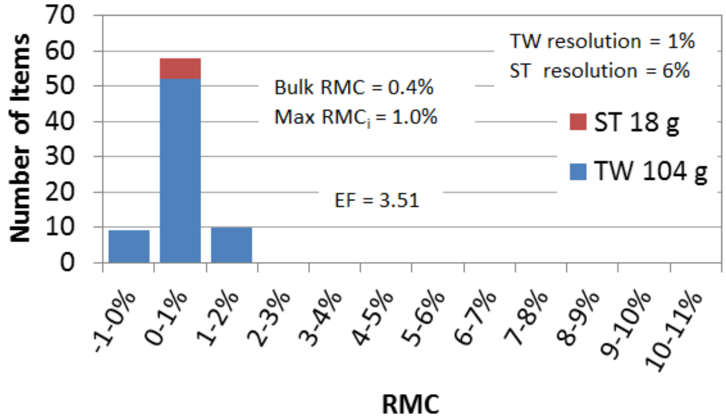

Fig. 23. RMC$_i$ for the DOE double-sized load.

6. DRYER CONTROLS EVALUATION

6.1 DESCRIPTION OF EXISTING CONTROLS

Conventional controls for dryers equipped with automatic termination rely on “moisture sensing bars” (two parallel metal strips, typically about six inches long and one inch apart) to sense the moisture content of the load. As the clothes tumble in the drum, they repeatedly fall against the bars. An electronic circuit measures the electrical resistance between the two bars. Because of the relatively high electrical conductivity of water, this measured resistance changes as the clothes dry.

An understanding of the controls of conventional dryers has emerged as follows:

- The dryer starts at full heating power.
- The dryer then modulates its heating output according to a thermostatic control to keep exhaust temperature below some threshold (see details in Table 10).
- The moisture sensor bar signal is reliable for indicating an RMC_{bulk} of ~10–25%. Below this RMC_{bulk}, the signal is not reliable. So the dryer goes into a “timed dry” mode at a moment determined from the moisture sensor bar signal.
    - The duration of this “timed dry” period might depend on user-selectable settings (such as fabric type, desired dryness, and load size).
- After this “timed dry” period ends, the dryer goes into “cooldown” mode (in which air continues to flow and the drum continues to tumble without heat input). Based on testing done in this investigation, a dryer can enter cooldown mode from 1 minute to more than 10 minutes after reaching an RMC_{bulk} of 1-3%.

Table 10. Summary of dryer controls

	Number of heating output levels (heating elements)	Thermostatic set point on high temperature (°F)
ES1	3	135
EC1	2	145
GS1	1	150
EC2	2	>140[a]
ES2	1	150

[a]For the EC2 unit, a low ratio of power output to airflow rate meant that, in the observed tests, no modulation was required in high heat mode. The two power levels were observed in an unreported cycle mode designed for delicate fabrics. The highest temperature seen in any tests was ~140°F.

Some minor variations, superimposed on the general pattern described previously, were observed:

- The ES1 consistently brings the exhaust temperature up to 100–110°F, then briefly (~1 minute) shuts off all three of its heating elements to allow a 5–10°F drop in exhaust temperature. After this, an algorithm seems to determine how many elements to keep on while the temperature slowly rises to the 135°F set point.

- The ES1 appears to select a power level that will hold the exhaust temperature at ~105–115°F until an RMC of ~10–20% is reached, when the exhaust temperature rises to ~135°F.

- The EC2 generally did not thermostatically modulate its output. This is most likely because of the low power (relative to air flow rate) of this model. The typical exhaust temperature was ~95°F, gradually rising to 125–140°F in the last 15 minutes or so of active heating.

6.2 PROPOSED MODIFIED CONTROLS

The two novel controls are based on observations made in RMC_i test results. These results indicate that, using conventional dryer operation, it might be necessary to hold RMC_{bulk} near ~1% to avoid having wet outlier items. It follows that, once the RMC_{bulk} reaches some threshold (perhaps 5–10%), what is needed is not so much additional drying but a homogenization of RMC_i among the items in the load. The intent of the novel controls is to accomplish the homogenization simultaneously with the last few percent reduction of RMC, with the goals of (1) increasing EF for a given $RMC_{i,max}$ outcome and (2) enhancing sensitivity of sensor response during the final stages of drying. As will be discussed later, it is not clear whether the modifications achieved these goals.

A conceptual illustration of the progression of EF, RMC_i, and RMC_{bulk} over cycle duration is shown in Fig. 24 (some supporting quantitative data are shown from tests on the ES1 dryer under D1 and D2 procedures using DOE cloth). The objective of the controls modification can be summarized as trying to find a strategy that would follow the dotted red line (with $RMC_{i,max}$ approaching RMC_{bulk} more quickly, leading to higher EF at a given $RMC_{i,max}$) instead of the conventional solid red line (with a much longer homogenization phase required). This would allow the dryer to turn off sooner under D2 operation and thereby achieve higher EF with acceptable $RMC_{i,max}$ and RMC_{bulk}.

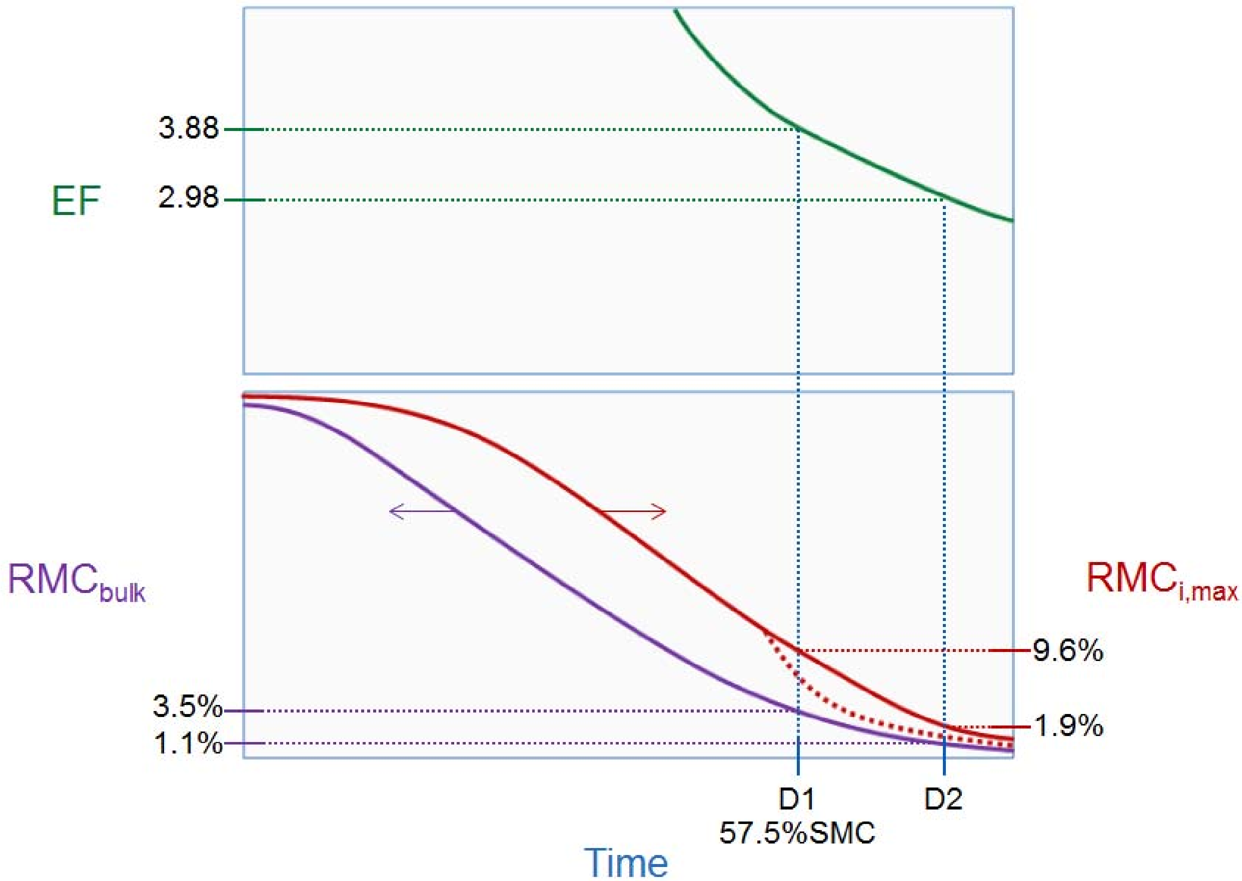

Fig. 24. Conceptual illustration of progression of EF and RMC over cycle duration.

In other words, the proposed controls would replace the current combination of

- the final 10 minutes (or so) of heating and cooldown

with one of the following:

- a 50% reduced airflow rate (accomplished via an exhaust damper in the lab and verified by reducing exhaust duct center velocity by 50%, as measured by a duct-mounted hot wire anemometer) or

- recirculation of all the exhaust back to the heater inlet (accomplished in the lab by redirecting all of the exhaust at the back of the dryer and only applicable to electric dryers).

To evaluate the reduced and recirculated methods, the dryers were run in timed dry, high-temperature mode. This means that the dryers were thermostatically modulating their heat input, near the values indicated in Table 10. With reduced or recirculated air, the heating elements would cycle more often and with lower average power input than with unmodified airflow. The dryers were not allowed to enter cooldown mode. The tests were stopped manually at a target final RMC_{bulk}.

The variables manipulated from one test to the next were (1) RMC_{bulk} at onset of reduced/recirculated airflow and (2) RMC_{bulk} at manual stoppage of dryer operation. In both cases, the RMC_{bulk} was determined by the real-time scale. A "cooldown period" without heating elements active was not used in the tests.

For a commercialized product, it is expected that the most inexpensive way to implement reduced airflow would be with a two-speed motor. However, to be suitable for gas dryers this might also require a two-stage combustion system. In addition, for gas and electric units, the potential effect of lower velocities on lint accumulation would need to be investigated.

Exhaust recirculation would be suitable only for electric dryers. It would require two exhaust flow paths with an actuated damper, and might present a design challenge (in terms of reliability and potential lint ignition since drum exhaust air would pass over the heater). In addition, the exhaust duct (from dryer to outside) would experience reduced velocity and, therefore, the effect on lint accumulation would need further investigation.

6.3 EVALUATION OF MODIFIED CONTROLS

The investigation of modified controls focused on a single dryer (ES1) and two loads (AHAM 2009 and DOE). The test matrix with key results is shown in Table 11. Even though manual termination was used on most of these tests, to allow for direct comparison with D2, the EF was calculated according to the D2 test procedure (final RMC compensation and field use correction were not applied to per-cycle energy consumption in the modified tests). Importantly, a cooldown period was not used in the modified controls here. It is suspected that a cooldown period would have improved the results of modified controls.

As seen in Table 11, the baseline results under D2 with AHAM 2009 were an EF of 3.18 +/- 0.16 (95% confidence interval [CI]) and RMC_{bulk} of 1.7 +/- 0.2% (95% CI), with an $RMC_{i,max}$ of 3.1%. To demonstrate an improvement, the modified control strategy would have to increase EF and keep RMC_{bulk} below the 5% threshold (ideally at or below the baseline value), while simultaneously reducing the $RMC_{i,max}$. To be statistically significant, EF would need to increase (from the baseline of 3.18) to above 3.34. These desired metrics were not achieved. Reduced airflow seemed to increase EF (though not enough to be statistically significant) but at the marked expense of $RMC_{i,max}$ (increasing to 9% or higher). Recirculation demonstrated statistically significant increases in EF but also at the expense of $RMC_{i,max}$.

Table 11. Summary of results with modified controls. The first six rows show unmodified tests for reference. All modified tests were conducted under high temperature setting

Test name	Modification	Modification introduced at [% RMC_{bulk}]	Cycle termination	Load	EF	RMC_{bulk}	$RMC_{i,max}$
1, 2, 3	None	N/A	Auto	AHAM 2009	3.18	1.7%	Not meas.
1R	None	N/A	Auto	AHAM 2009	3.03	1.7%	3.1%
9, 10, 11	None	N/A	Auto	DOE	3.19	0.8%	Not meas.
9R	None	N/A	Auto	DOE	2.98	1.1%	1.9%
13, 14, 15	None	N/A	Manual	DOE	4.06[a]	3.7%	Not meas.
13R	None	N/A	Manual	DOE	3.88[a]	3.5%	9.6%
M1	Reduce air	5%	Manual	AHAM 2009	3.27	3.5%	19%
M2	Reduce air	10%	Manual	AHAM 2009	3.28	2.5%	9%
M3	Reduce air	15%	Manual	AHAM 2009	3.30	2.4%	8%
M4	Reduce air	15%	Auto	AHAM 2009	3.18	1.6%	4.0%
M5	Recirc air	8%	Manual	AHAM 2009	3.36	3.4%	13%
M6	Recirc air	8%	Manual	AHAM 2009	3.49	3.3%	8%
M7	Recirc air	12%	Manual	AHAM 2009	3.24	2.4%	10.3%
M8	Reduce air	10%	Manual	DOE	3.88	3.1%	14%
M9	Reduce air	20%	Manual	DOE	3.94	3.5%	10.7%

[a]Final RMC compensation and field use correction factor not applied to the EF shown in this table to facilitate direct comparisons.

For purposes of evaluating the effect of the modified controls on RMC_i distribution, Figs. 25 and 26 show the RMC_i scores for all the tests on which RMC_i was measured, some with baseline controls and some with modified controls. The tests with the AHAM 2009 load are in Fig. 25, and the tests with the DOE load are in Fig. 26. If the modifications were successful in reducing the RMC_i distribution for a given RMC_{bulk}, the modified tests should tend to lie lower in the diagram than the baseline results. From Figs. 25 and 26 it can be seen that the tests with modified controls did not achieve a lower $RMC_{i,max}$ for a given RMC_{bulk}. However, it may still be possible that the modified controls provide an advantage because the shifts in $RMC_{i,max}$ appear to be accompanied by increases in EF, although the lack of directly comparable final RMC_{bulk} values among tests precludes a definitive conclusion. For example, in Fig. 25 test M4 had higher EF than test 1R, but unfortunately M4 was stopped just before its RMC_{bulk} reached the value of 1R, so it cannot be known what the EF would have been at comparable RMC_{bulk} values. The case of tests M9 and 13R in Fig. 26 is similar.

Of course the simple RMC_i scoring metric used does not capture everything about the distribution of individual RMCs. Tests 13R and M8 both had about the same bulk RMC—3.5 and 3.1%, respectively. They also had identical EFs of 3.88 and similar RMC_i scores—16 and 20, respectively. This means that at the same EF the modified controls had a lower bulk RMC (a desirable feature) but a higher RMC_i score of items above 5% RMC_i (an undesirable feature).

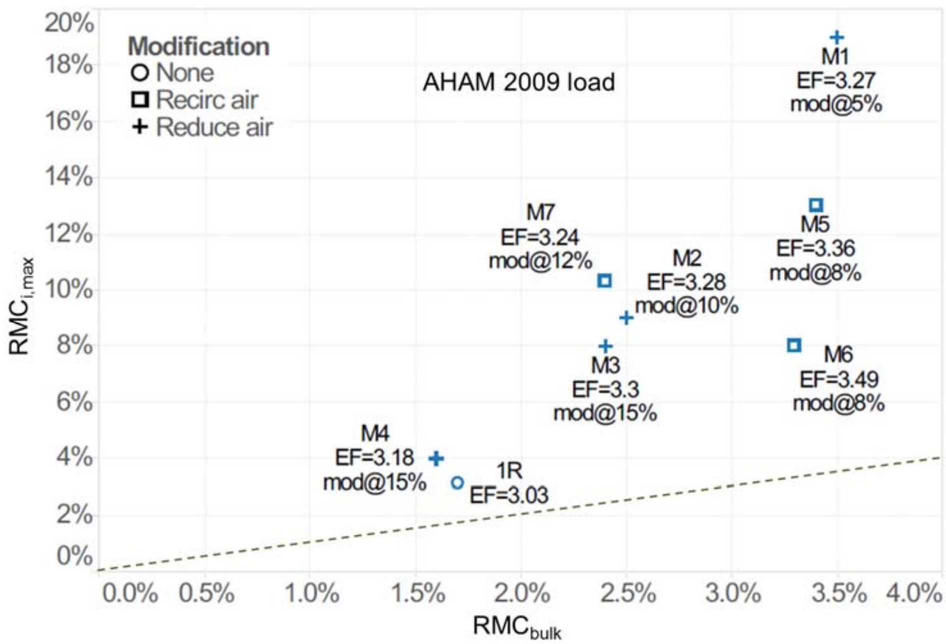

Fig. 25. $RMC_{i,max}$ vs. RMC_{bulk} for baseline (circles), recirculated airflow (squares), and reduced airflow (plusses) tests with AHAM 2009 load. Dotted line shows ideal limit of uniform RMC_i. Labels for each test show test name, EF value, and when in the cycle the modification was introduced (at what value of %RMC).

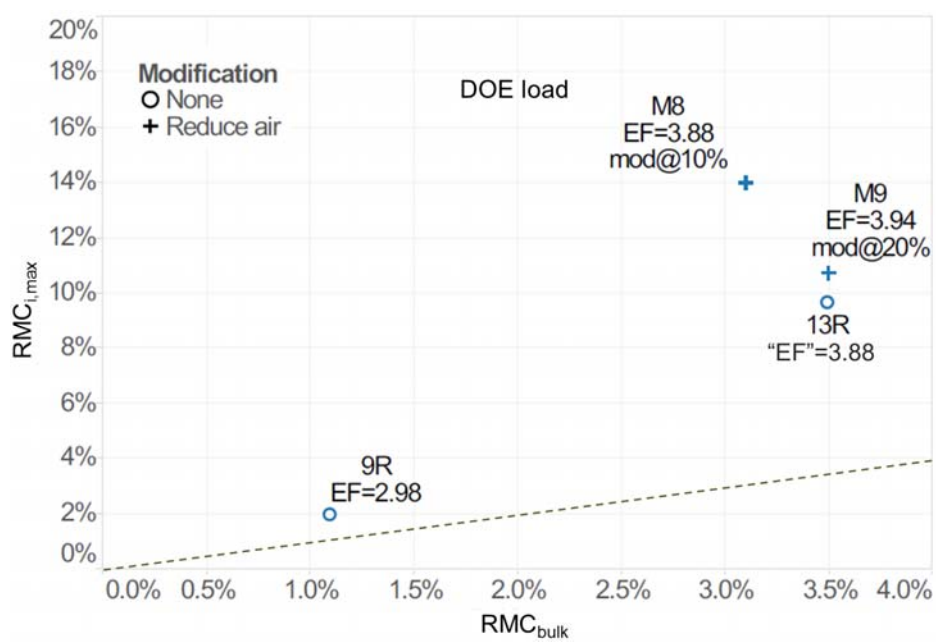

Fig. 26. $RMC_{i,max}$ versus EF for baseline (circles) and reduced airflow (plusses) tests with DOE load. Dotted line shows ideal limit of uniform RMC_i. Labels for each test show test name, EF value, and when in the cycle the modification was introduced (at what value of %RMC).

The full distribution of RMC_i is shown for tests 13R in Fig. 27 and for test M8 in Fig. 28. The excess RMC_i score was 15 for test 13R and 20 for test M8.

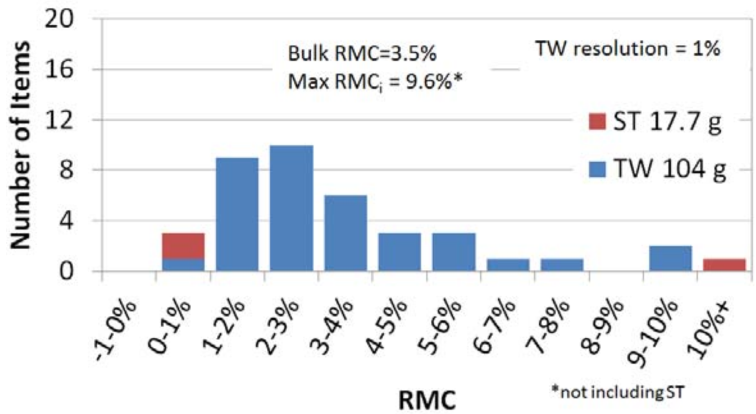

Fig. 27. Individual RMC histogram for test 13R (a baseline timed-dry D1 test).

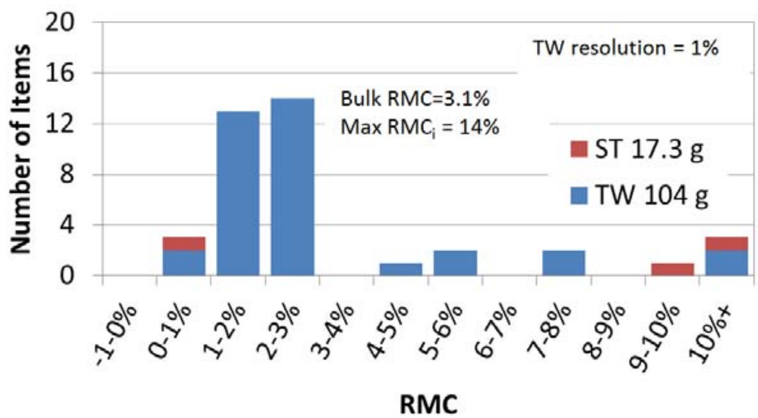

Fig. 28. Individual RMC histogram for test M8 (reduced airflow starting at 10% RMC).

Figure 29 presents the modified controls in a different way and shows the evolution of bulk RMC with exhaust humidity over the course of a test. It shows two baseline tests and two modified tests (with reduced airflow).

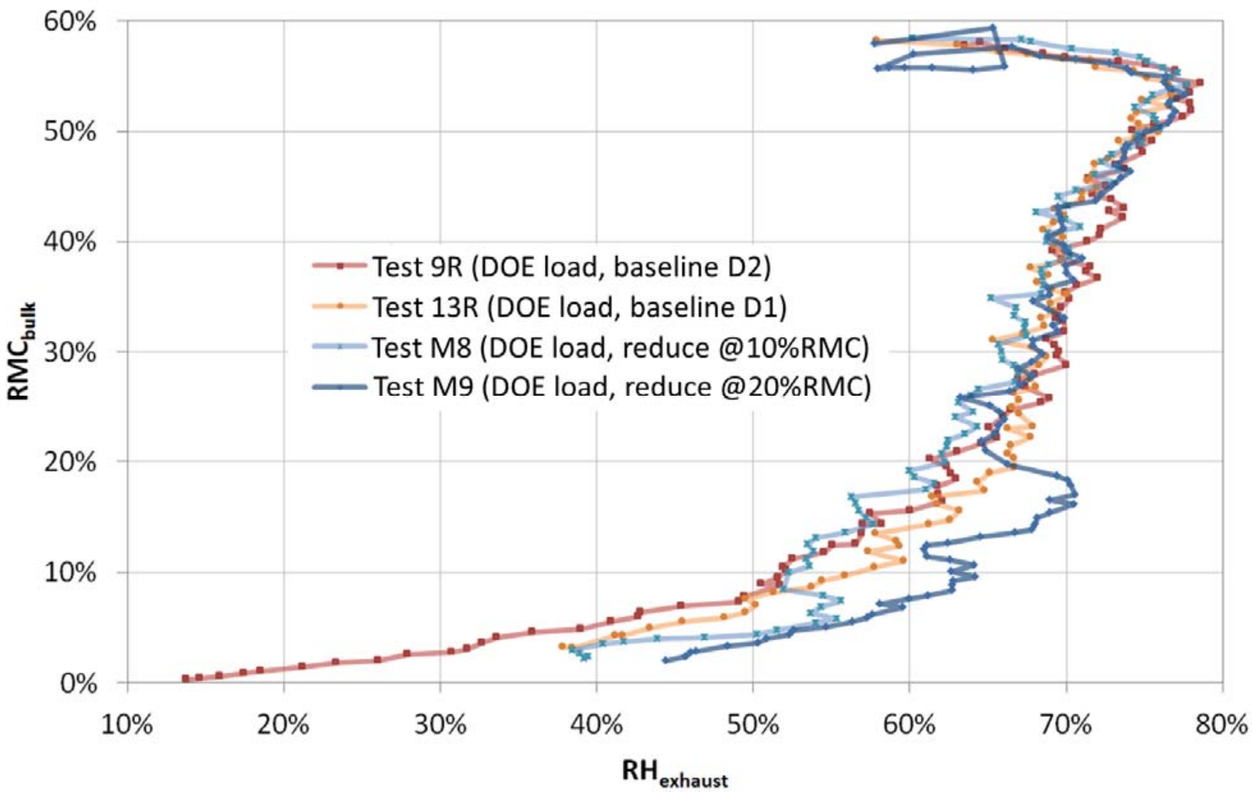

Fig. 29. Real-time RMC_{bulk} vs. exhaust relative humidity for baseline tests and modified tests with DOE load.

It would seem that exhaust relative humidity (RH) would be a relatively reliable indicator of final RMC for both baseline and reduced airflow tests. For example, a dryer might use the conventional control scheme outlined in Sect. 6.1 but use an RH sensor instead of moisture-sensing bars to determine when to enter the timed dry mode. Referring to Fig. 29, if using a sensor with +/-10% accuracy and using 30% exhaust RH as a target threshold, the RH sensor approach would predict the RMC to be approximately 1–6% for test 9R. Using 40% RH as a target threshold, the RH sensor approach would predict the RMC to be approximately 2–5% in the case of test M8.

Another look at baseline and reduced airflow tests is shown in Fig. 30. Here it can be seen that compared with the baseline tests the RMC drops faster for the same energy consumption with reduced airflow. The effect was more pronounced with the test that began reducing airflow sooner.

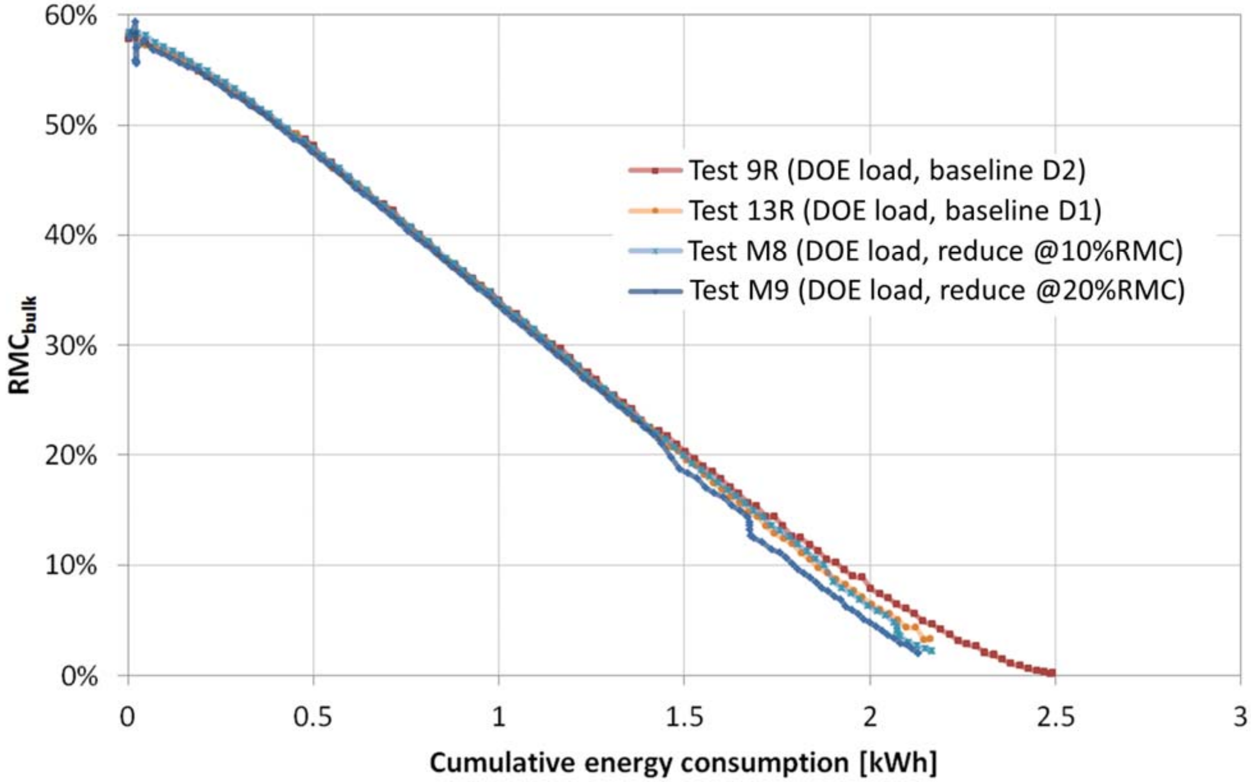

Fig. 30. Real-time RMC vs. cumulative energy consumption for two baseline and two reduced airflow tests.

7. CONCLUSIONS

In this study high quality data were acquired and documented to help inform stakeholders about how dryer performance would be characterized under the D1 and D2 test procedures. This information might provide a better foundation for improving the performance of residential clothes dryers in the future.

This work investigated two standard size electric dryers, two compact size electric dryers, and one standard size gas dryer. All dryers used a tumble-type drum with forced air circulation to dry clothes. All dryers were of the vented type, where air is sourced from inside the conditioned space of the home and after passing through the drum is exhausted through a duct to the outdoors.

Tests in accordance with Appendixes D1 and D2 were conducted to determine three performance metrics—final RMC_{bulk}, EF, and cycle duration—and the repeatability of those metrics when dryers are retested. Summary observations from the data are as follows:

- Compared with tests under D1, each dryer's EF was 7–22% lower under D2, which is only partially explained by the lower RMC_{bulk} involved in the D2 test procedure.
- Compared with tests under D1, each dryer's cycle duration was longer under D2.
- Mixed results were found for the repeatability of EF under D1 and D2 (for one dryer D1 was more repeatable, and for another dryer D2 was more repeatable).

Tests in accordance with D2 were also conducted using three different clothing loads—DOE, AHAM 1992, and AHAM 2009—to ascertain the influence of load on the same three performance metrics. Summary observations from the data are as follows:

- The RMC_{bulk} of each dryer's clothing load decreased from AHAM 1992 to AHAM 2009, and decreased again from AHAM 2009 to the DOE load.
- Among the three load types, each dryer's D2 EF was lowest with the AHAM 2009 load. Depending on the dryer, the EF might be highest with either the AHAM 1992 or the DOE load.
- In general each dryer's cycle duration did not vary much across the three loads.
- Comparing dryer models to each other, relative EF and RMC performance with the DOE load was a good predictor of relative performance with the other loads.
- When placed in automatic termination and normal dryness setting, all five dryer models evaluated were able to dry to less than 2.0% RMC_{bulk} with the DOE clothing load. Only one model was able to dry to <2.0% under normal dryness with the AHAM 1992 load, and three were able to do so with the AHAM 2009 load.

The D1 and D2 test procedures both use RMC_{bulk} as a performance metric. The DOE test load contains 39 individual pieces of clothing, the AHAM 2009 contains 22, and the AHAM 1992 contains 16. In this study some effort was expended to examine the RMC of individual pieces of clothing in the load (RMC_i). Only limited testing was conducted but insights from this data may suggest strategies for dryer performance improvement.

This work also included preliminary investigations of automated cycle termination concepts not currently used in commercially available residential clothes dryers. Comparison of RMC_{bulk} and RMC_i data suggested that perhaps once RMC_{bulk} reaches some threshold, what is needed is not so much additional drying but a homogenization of RMC_i among the items in the load. Although the preliminary concepts evaluated here did not demonstrate clear benefits over existing approaches, this might be an avenue for improving dryer efficiency in the future.

8. REFERENCES

AHAM 1992. Test cloth detailed in AHAM publication HLD-1-1992, "Household Tumble Type Clothes Dryers."

AHAM 2009. Test cloth detailed in AHAM publication HLD-1-2009, "Household Tumble Type Clothes Dryers."

10 CFR 430 2013. *US Code of Federal Regulations*, Title 10: "Energy"; Part 430, "Energy Conservation Program for Consumer Products"; Subpart B, "Test Procedures"; Appendix D/D1/D2, "Uniform Test Method for Measuring the Energy Consumption of Clothes Dryers" (DOE test procedure and test cloth).

APPENDIX

A.1 SUPPLEMENTAL INFORMATION ABOUT TEST LOADS

Additional information about the test loads is provided in the following.

The as-received measured bone dry weights matched very closely with the weights expected from the catalog for DOE and AHAM 2009. However the test cloth provider's AHAM 1992 cloths had some deviations from the expected weight. The weights are shown in Table A.1 and the weight deviations are plotted in Figure A.1 below.

Table A.1. Load types used

Test cloth	Allowable weight-averaged age of load	Items included					
		Description	Alias	Typical BDW [lb]		Items used (8.45 lb load)	Items used (3.00 lb load)
				Catalog	Meas-ured		
DOE	0-24 cycles (uniform ages)	towels	TW	0.231	0.229	36	13
		washcloths	ST	0.041	0.039	3	0
AHAM 1992	0-25 cycles (uniform ages)	sheets	SH	1.32	1.71	2	0
		table cloths	TC	0.69	0.69	1	0
		bath towels	TW	0.57	0.62	3	1
		long sleeve shirts	SR	0.49	0.60	2	2
		T-shirts	TS	0.29	0.30	2	1
		pillowcases	PC	0.27	0.16	1	1
		shorts	BX	0.26	0.20	2	2
		wash cloths	WC	0.065	-[a]	0	1
		handkerchiefs	HC	0.034	0.031	3	3
AHAM 2009	29-51 cycles (with specific age distribution)	sheets	SH	1.50	1.49	2	0
		pillowcases	PC	0.48	0.48	4	2
		towels	TW	0.22	0.22	16	9

[a]Not used since it was not required to fine tune load weight.

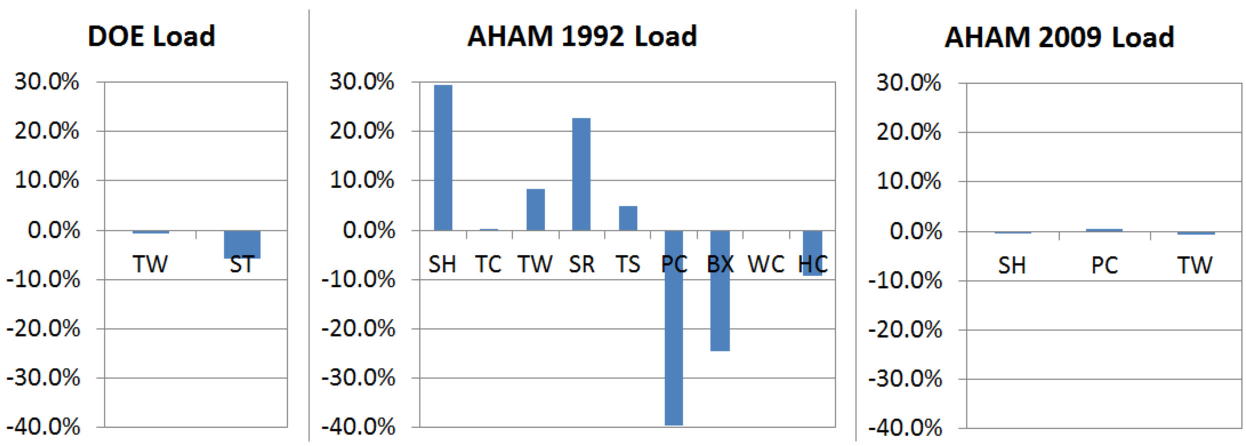

Fig. A.1. Measured weights (BDW) vs. catalog weights of cloths used in testing.