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Clothing Wear and Tear of Heat Pump vs. Electric Resistance Clothes Dryers

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Executive Summary

Heat pump clothes dryers are significantly more energy efficient than conventional electric resistance clothes dryers. The goal of this project was to determine whether heat pump clothes dryers offer non-energy benefits—specifically, reduced clothing wear and tear—that could help consumer adoption. If this can be shown, it may help market transformation efforts that would produce significant energy savings in this appliance type that has been largely overlooked compared to other appliances.

Clothing wear and tear tends to be reduced by lower drying temperatures, and increased by the longer tumbling time. We prepared five identical loads of diverse garment types and fabrics in order to investigate these effects. One load was the control. We ran the other four loads 25 times on a short cycle in the clothes washer (without soap) and then dried them. The first of these loads was dried in a pure heat pump dryer. The second load was dried in a hybrid heat pump dryer, which also employs electric resistance elements as a booster. The third load was dried in a conventional electric resistance dryer with high washer spin speed (like the first and second loads). The fourth load used a slower spin speed in the washer—to be more representative of the current washer market—and then dried in the conventional dryer.

This project did not conclusively find that heat pump clothes dryers cause less wear than conventional dryers. However, the study was able to show that they do not cause more wear than conventional dryers. Tensile testing was largely inconclusive, as was photomicrograph investigation. A consumer evaluation session revealed a preference for the hybrid heat pump dryer, and a slight dis-preference for the pure heat pump dryer. The consumers were generally satisfied by the results from all dryers overall. As expected, high spin speed in the washer reduced overall laundering cycle times.

We recommend consideration of further testing to determine whether there is a difference in wear and tear between ENERGY STAR and non-ENERGY STAR dryers, the main difference being the effect of auto-termination. It may also be helpful to study the impact of initial moisture content on wear and tear.

Introduction

Heat pump clothes dryers offer energy efficiency benefits that have helped them gain significant market share in Europe, but the technology is a relatively new entrant to the U.S. market. While conventional electric clothes dryers use electric resistance as their heat source, heat pump dryers use a refrigeration-cycle dehumidifier to heat and dry the air circulating in the drum with the clothes. Because of the efficiency of the refrigeration process and the recycling of heat, these dryers typically reduce energy use and operating cost by 50–60 percent compared to conventional dryers.[1]

Despite this energy savings, consumer acceptance of heat pump dryers in the U.S. has been low because of two factors: higher initial cost and limited retail availability and awareness. The prospective energy benefits of this technology have led utilities and policy makers to look for other factors that may encourage wider consumer acceptance. To this end, the Northwest Energy Efficiency Alliance (NEEA) and the Pacific Gas & Electric Company (PG&E) commissioned a study to evaluate the possibility that heat pump dryers preserve the quality of clothing and extend their useful life.

The expectation of reduced clothing wear from heat pump dryers arises from the fact that they operate at lower temperatures compared to conventional electric dryers (and compared to natural gas and propane dryers, which were not part of this study). The detrimental effect of high temperature on fabrics has been well documented.[2] While a conventional electric resistance dryer typically operates at maximum fabric temperatures of around160°F, heat pump dryers rarely exceed 120°F.

It has also been shown that the act of tumbling clothes in the dryer can cause clothing wear.[3] Because heat pump dryers run at lower temperatures but tumble for longer periods, it is not clear which effect is dominant, or if either is significant enough to be measured in a comparison of these two technologies. This study was designed to isolate the effects of tumble time and operating temperature, while attempting to minimize other influences, such as different washer types.

The influence of the washer cycle on dryers must be considered, however. Modern front-loading washers have high spin speeds that reduce dryer workload by wringing more moisture out of the clothes. Although research shows that most dryers are purchased as part of washer-dryer pairs,[4] and most new washers have high-spin-speed capability, we wanted to also test dryer performance when starting with the wetter clothes that still come out of many U.S. washing machines. For this reason—and because we studied a load with mixed weight and fiber types—we tested one load with a low spin speed to produce a higher moisture content entering the conventional dryer (see Appendix). This “low-spin-speed” load, sent to the exact same conventional dryer as a “high-spin-speed” load, attempted to isolate the effects of tumbling time for a direct comparison.

Background

Previous research on the impact of laundering on garments has included a number of studies that focus on the dryer. The study by Buisson, Rajasekaran K., French, Conrad, and Roy (2000) provides the best example of a recent exploration of the impact of drying on garments.[2] They found that while tumble drying reduces fabric strength, the application of heat during the tumbling

exacerbates this strength reduction, particularly at the end of the cycle. Removing heat after an RMC[1] of 4% has the most beneficial effect on preserving strength in heat-dried textiles.

Tumbling abrasion, including drum-to-garment and garment-to-garment contact, also damages textiles. For example, fabric-to-fabric abrasion tests have demonstrated that a loose weave shows abrasion much sooner than a heavy twill weave.[5] An examination of various laundering methods on fabrics with wrinkle-resistant finishes found that high levels of these finishes causes fibrillation in the fibers which have been embrittled with cross-linking agents.[6] Researchers who explored this effect determined that while over-drying does embrittle the fibers, drying from an overly wet state increases the damage, suggesting that reducing moisture prior to drying and turning off heat before over-drying are both important to reducing fiber damage.[7] On the other hand, a study of the impact of drying time and temperature on knitted and woven cotton fabrics showed that the increased tumble time required at lower temperatures may increase wrinkling.[3]

Of course, laundering is not the only cause of wear on garments. Research by textile scientists at UC Davis compared trousers laundered 60 times and worn by staff members for 2 days between each cycle to trousers laundered for 60 cycles but with no actual human use. They found that about 50% of wear was due to laundering and 50% due to use.[8] Their study also found that ending drying at 5% RMC produced better results than continuing with heat for a lower RMC. Another study that included more fabric types in their test loads concluded that cotton/polyester blends were less vulnerable to abrasion than cotton treated with wrinkle resistant finish.[9]

Test Methodology

Washer and Dryer Model Selection

At the time we conducted the study, three heat pump equipped dryers were offered in the United States: one vented hybrid, one ventless[2] hybrid[3] and one pure heat pump model. We chose to test the pure heat pump because it represented the class of lowest-temperature dryers, and the unvented hybrid because it was sold by a well-known manufacturer with a potential for gaining traction with consumers. For the conventional dryer, we chose the a unit of the same model family as the hybrid, since it is similar to the hybrid in its design, construction, and controls, but uses only electric resistance heat. This dryer is ENERGY STAR rated, so it does include some performance advantages compared to other conventional dryers (such as better auto-termination control).[10]

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[1] "RMC" refers to remaining moisture content, a common indicator used in dryer energy and performance testing. Here the RMC is relative to bone dry.

[2] Ventless dryers recycle air instead of exhausting warm moist air to the outdoors. The air exiting the drum goes through a heat exchanger that captures sensible heat (reducing the air's temperature) and latent heat (condensing the moisture out of the air). The heat pump then reheats the air and sends it back into the drum. Instead of an exhaust duct, ventless dryers have a drain pipe that carries away the condensed water.

[3] The terms "pure" and "hybrid" are used in this paper as follows: a *pure* heat pump dryer has no electric resistance element to provide heat, and uses only the refrigeration cycle of the heat pump to dry. A *hybrid* dryer has both the heat pump equipment and a resistance heater that injects heat into the system.

Clothing Selection

We selected eleven clothing items used for this study for specific reasons, with the overarching rationale being the desire to see a "wear signal" after subjecting the loads to multiple wash-dry cycles. We chose common garments likely to be laundered often—t-shirts, jeans, and work shirts—and avoided specialty garments such as suit coats or evening dresses that would likely be dry cleaned (see Table 1 below). To test a variety of fabric types, we included cotton, polyester, rayon, and nylon garments. Two different brands of jeans were chosen to potentially identify differences in fabric durability, and the slip and flannel pajamas were chosen as likely to show wear and fabric weakening. We avoided low-value garments that tend to be discarded relatively quickly, such as socks and common underwear. The garments that made up each load are shown in **Table 1**.

Table 1: Load Composition

Garment	Material
Polo shirt	50% polyester/50% cotton
Dress shirt	100% cotton
Chambray shirt	100% cotton
Men's work shirt	50% polyester/50% cotton
Sweater	78% acrylic/22% nylon
Flannel pajama bottoms	100% cotton
Half-slip	97% nylon/3% spandex
Women's blouse	100% rayon
Blue jeans "A"	98% cotton/2% spandex
Blue jeans "B"	100% cotton
T-shirt	50% polyester/50% cotton

With five loads and eleven garments per load, a total of fifty-five garments were used in the study. We purchased all garments new by online ordering, and sourced each garment type as one shipment from a single vendor, so there should be negligible variations between garments of a single type; all of the polo shirts, for example, likely came from the same batch of fabric if not the same bolt.

Test Method Design and Dryer Controls Selection

We examined the effects of using the three different dryers described above, and tested a total of five loads of identical garments. **Table 2** below provides a summary of the five test loads.

Table 2. Load Comparison Parameters				
Test #	Test ID	Load Description	Dryer Used	Spin Speed/Starting Moisture
1	CL	Control	n/a	n/a
2	C	Conventional Wet Start	Conventional resistance	Slow/wet (~63% RMC4)
3	CF	Conventional Damp Start	Conventional resistance	Fast/damp (~42% RMC)
4	H	Hybrid heat pump	Hybrid heat pump	Fast/damp (~42% RMC)
5	B	Pure heat pump	Pure heat pump	Fast/damp (~42% RMC)

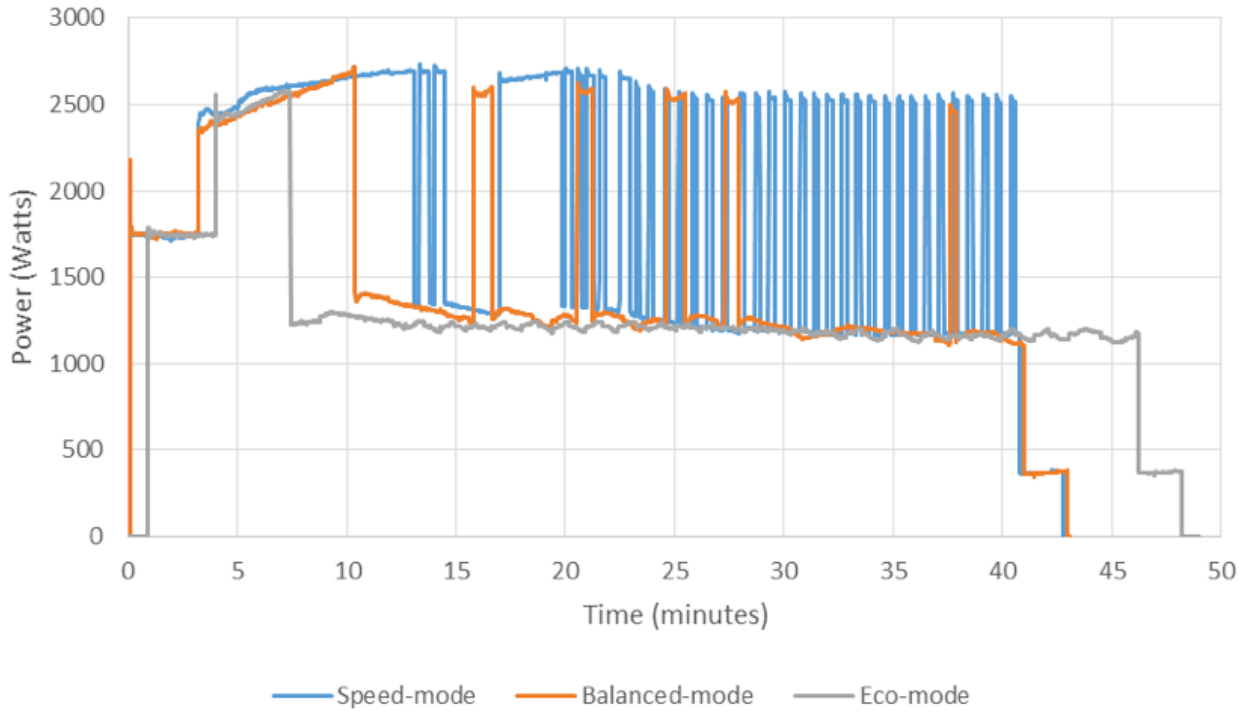
We preconditioned all loads by running them through a regular washer cycle with warm water and reference detergent5 and one dryer cycle. Because the goal of the study was to examine consumer acceptance, rather than to conform to specific testing methods, lab staff subjectively evaluated each item in the preconditioning load for dryness using a 1 to 5 scale with 1 being wet, 4 being acceptable to consumers and 5 being completely dry. While this evaluation revealed that there were parts of the 100% cotton blue jeans that were still damp for both the pure heat pump and the hybrid dryers, the rest of the loads were acceptably dry and, based again on the replication of a consumer setting and concern about damaging the more delicate items by using the "more dry" setting, we selected the "normal dry" setting for the testing.

For the conventional and hybrid dryers, the wrinkle shield feature intermittently tumbled the clothing after the cycle. This functionality was disabled to isolate the clothing wear and tear of the cycle proper. On these dryers, "eco-boost" was the default setting, meaning it would be evaluated by the DOE test procedure with this energy-saving mode enabled. This mode extends the drying time. We reasoned that the users of a hybrid heat pump dryer would be more interested in saving energy than saving time, so we ran the tests with eco-boost enabled. However, for the conventional dryer, we turned off eco-boost to make the dryer perform similarly to other conventional electric resistance dryers.

The power trace of the hybrid dryer in the speed, balanced, and eco-boost modes is shown in **Figure 1**. The heat pump remains on nearly all of the time for all of the runs. In eco mode, electric resistance only runs in the beginning, and total drying time takes about five minutes longer than the other modes. In balanced mode, the resistance element runs for about a minute every five minutes during the middle of the cycle. In speed mode, the resistance heater comes on in brief intervals throughout the cycle. Total drying time was the same for balanced-mode and speed-mode operation. We measured power for these initial runs (with clothing that was not part of the actual study), and only for the hybrid dryer, to inform selection of the operating mode for testing that dryer.

[5] Per Department of Energy (DOE) or American Association of Textile Chemists and Colorists (AATCC) standards.

Figure 1: Power Trace for the Hybrid Heat Pump Dryer in Different Modes



After we finished preconditioning, we set aside the control load, and then subjected Loads 2-5 to twenty-five cycles of washing and drying. We tested garments in various ways at the beginning and end of the 25 cycles, and also performed some tests at stages along the way. Because we were interested in dryer rather than washer effects, we washed the loads with a quick cycle and no detergent through the 25 cycles.

Control mechanisms on dryers have become increasingly complex with the advent of sensor technology that can monitor the temperature, moisture content, and even weight of the laundry in the drum. Efforts by the DOE to increase energy efficiency, and by appliance manufacturers to increase consumer satisfaction, have led to dryer control panels that can be rather opaque in their actual consequences in terms on dryer operation. Options such as “wrinkle free” or “eco” help the consumer focus on the desired results rather than having them choose a specific temperature (high, medium, low) or duration (minutes). This shift means that the settings available on new dryers typically consist of a program (e.g. normal or cottons), a temperature setting, a final dryness setting, and optional settings such as energy-saving or wrinkle prevention (tumbling after the cycle has completed). The goal of this study was to replicate an average, rather than extreme, consumer situation. For this reason, we used the normal or cottons program, and when possible, chose the medium temperature and normal dryness options. See the Appendix tables for details of all settings used for the study.

Test Plan Details

Table 3 shows the measurements taken on the clothing samples.

Table 3. Clothing Measurements Taken

Test #	Description	Test Interval
Weight	Weight of wet load, dry load, and individual clothing samples.	Every 5 cycles
Color	Spectrophotometer readings of clothing.	After 0 and 25 cycles
Appearance	Photos used for subjective evaluations	After cycles 0, 3, 5 and 25 cycles
Consumer Acceptance	Review by 5 consumers for general impact and appearance changes including: • Seam Smoothness • Puckering • Frosting • Abrasion • Hand	Control load and all 4 loads after 25 cycles
Fiber Strength	Samples extracted from clothes and subjected to destructive testing	After 25 cycles
Micro Photography	High resolution, high magnification of clothing fibers with reference object(s) • Fiber shape and structure changes • Fiber damage and breakage	After 25 cycles

Time, Temperature, and Weight

We placed thermally sensitive stickers on the polo and work shirts, the flannel pajama bottoms and the cotton/spandex jeans during the preconditioning, and cycles 5 and 15. These stickers recorded the highest temperature in intervals of 10°F.

A loss of weight during laundering, following the initial preconditioning, would signal damage to the garments due to the fiber loss. In addition, weighing the loads before and after drying would indicate how much energy was required for drying based on how much moisture was removed from the garment. We used a calibrated scale for the weighing. The initial moisture content (IMC) percentage going into the dryer was calculated relative to the bone dry weight6:

$$IMC = ((Initial\ Weight - Bone\ Dry\ Weight)/Bone\ Dry\ Weight)*100\%$$

Similarly, the remaining moisture content (RMC) coming out of the dryer is calculated by:

$$RMC = ((Final\ Weight - Bone\ Dry\ Weight)/Bone\ Dry\ Weight)*100\%$$

[6] To limit unrealistic clothing wear and tear, the loads were never bone dried (dried repeatedly to approach zero moisture). Instead, an initial bone dry weight of the load was calculated as follows. In the International Electrotechnical Commission (IEC) clothes dryer test procedure, initial equilibrium occurs at 65% relative humidity, at which point 100% cotton articles have 6% moisture content relative to bone dry and 35% cotton articles have 2.5% moisture content. Our articles were equilibrated at 50% relative humidity, so we scaled the initial moisture down linearly. The weighted average for the load would then have 3.3% initial moisture at equilibrium in our lab. We thus subtracted this amount of moisture from our intial equilibrated weight to arrive at the calculated bone dry weight.

A calculation of the percentage of moisture removed during drying, also based on bone dry weight, was the difference between IMC and RMC.

Color

The CIE[7]Lab color measurements were taken on specific locations of selected garments using a Hunter Lab LabScan model XE spectrophotometer immediately following preconditioning and again after the final (25th) load. Calculation of the basic ΔE (the difference between two colors as measured by the distance between their coordinates in a three dimensional color space) was made using the most straightforward (1976 CIE) formula, given that the intention of the measurement was simply to identify differences in color change between the drying methods, not to determine the absolute amount of color loss or transfer.

$$\Delta E = \sqrt{(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2}$$

Color

The tensile strength of selected garments was measured using an Instron 4400R testing machine. The testing procedure generally followed ASTM D5034[8], with slight variations. We cut test samples sized 3"x6" from six of the garments in each load, with the long dimension containing the warp yarns of the garments. We tested three samples from each garment tested, staggered so that different yarns were tested in each sample. We prepared the samples after being given time to adjust to the local temperature and humidity levels. We notched the samples to create a 1" wide testing strip for the tensile force to concentrate, which resulted in most samples breaking at the notch, indicating a good test. Data were recorded by noting the maximum breaking force on the Instron control panel, and by referring to data streamed to LabView and stored in spreadsheet format. The loading rate was 2" per minute, which resulted in break times of approximately 30 seconds per test, which is consistent with the ASTM D5034 process.

Appearance

Lab staff took photographs of portions of selected garments—focusing on the seams, collars, cuffs and hems—in a standardized setting after the preconditioning and cycles 3, 5 and 25. The photo setup was against a gray background using the evaluation settings described in AATCC Test Method 124. Each garment was labeled with a random number in each photograph that was keyed to the load and dryer in a separate list, allowing for blinded evaluation of the photos for frosting, puckering and abrasion. Photographic replicas for seam smoothness served as a basis for the evaluation of the seams, while the general principles of AATCC subjective evaluation were the basis for other areas of the garments. These principles are that, on a 1 to 5 scale, the rating of 1 is given for the very worst examples of a condition, while 5 is given for near perfection. The rating of 4 represents what would be slightly noticeable but acceptable to the average consumer and the rating of 3 would be definitely noticeable and unacceptable to the consumer. Using these principles, each blinded photo was assigned a rating from 1 to 5 and then the key was applied to order the ratings based on load type and cycle number.

[7] CIE is the English-language abbreviation for the International Commission on Illumination.

[8] Standard Test Method for Breaking Strength and Elongation of Textile Fabrics (Grab Test)

Consumer Acceptance

For the subjective evaluation, we held a session with a small group of consumers who were not professionals (i.e. not in the business of laundering or textiles). The consumers received a brief introduction and provided vocabulary sheets with terms like "hand", "frosting" and "abrasion." They then examined each garment in each load, making notes about their impressions of the wear and tear on the garments. They understood that their opinions would be recorded, and all signed a recording release and participation consent form. We did not initially inform the participants about the purpose of the study, but told them only that "different laundering methods were used" for the various loads. To reduce order bias, we identified the loads with random letters. During the individual evaluation portion of the session, each evaluator wrote their notes on clipboards without any discussion with the other evaluators. Following the silent evaluations, one of the researchers and an assistant conducted a guided discussion where the participants shared additional opinions both about the results of the study as seen in the garments as well as about consumer acceptance of energy-efficient appliances. Then there was a discussion period when the consumers offered additional opinions and observations.

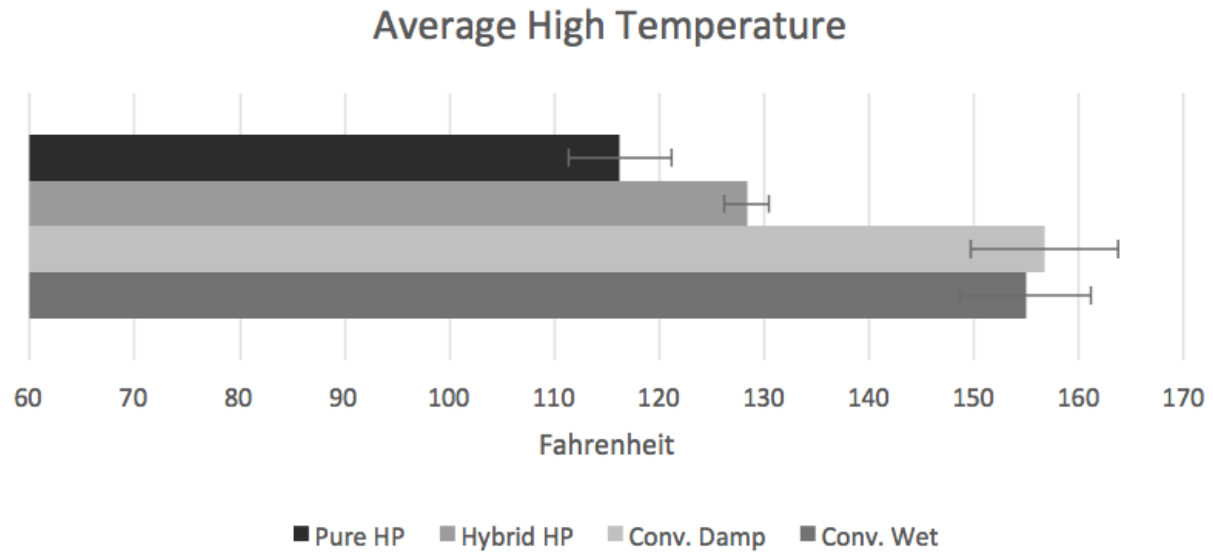
Results

The goal of this study was to determine if heat pump clothes drying reduced clothing wear relative to conventional electric resistance drying. The study also attempted to isolate and compare the effects of temperature and tumbling time in the different dryers and loads. Examination methods included load weight comparisons, spectrophotometry, subjective evaluation, consumer evaluation, tensile testing and photomicrography.

Time, Temperature, and Weight

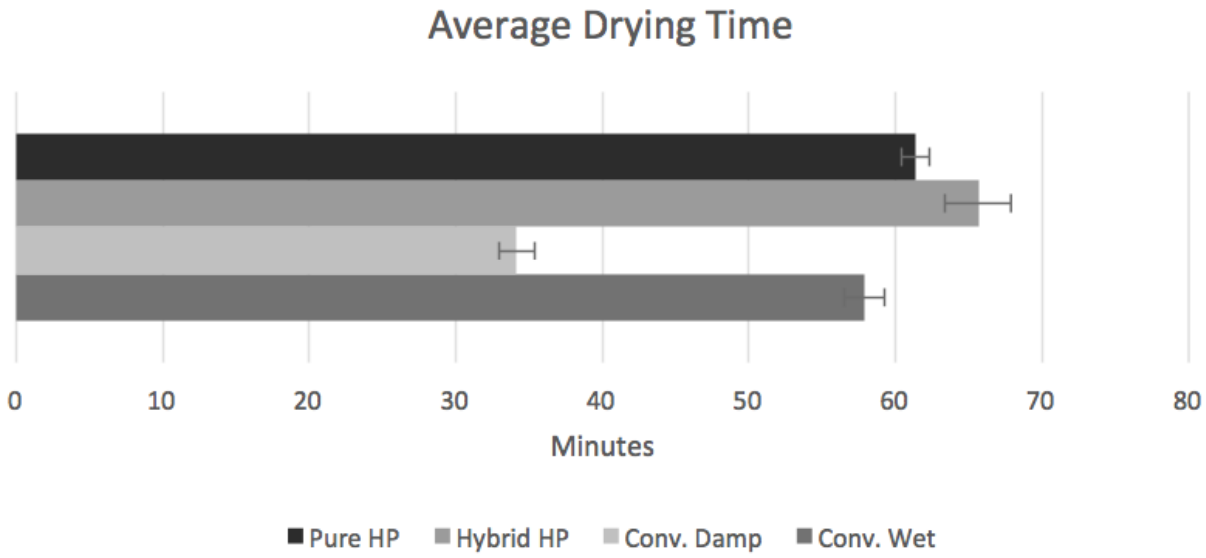
As expected, the conventional dryer reached the highest temperatures (see Figure 2) and required the least amount of time in a direct comparison. The hybrid HP dryer temperature was slightly higher than the pure heat pump dryer—not surprising since the hybrid injects some electric resistance heat. The fact that the hybrid HP reached around 130°F is suggestive given that previous studies11 showed that most moisture loss from cotton occurs at or below 128°F and, by weight, cotton (e.g. jeans) comprised a majority of the load.

Figure 2: Maximum Fabric Temperatures (error bars are 95% confidence intervals)



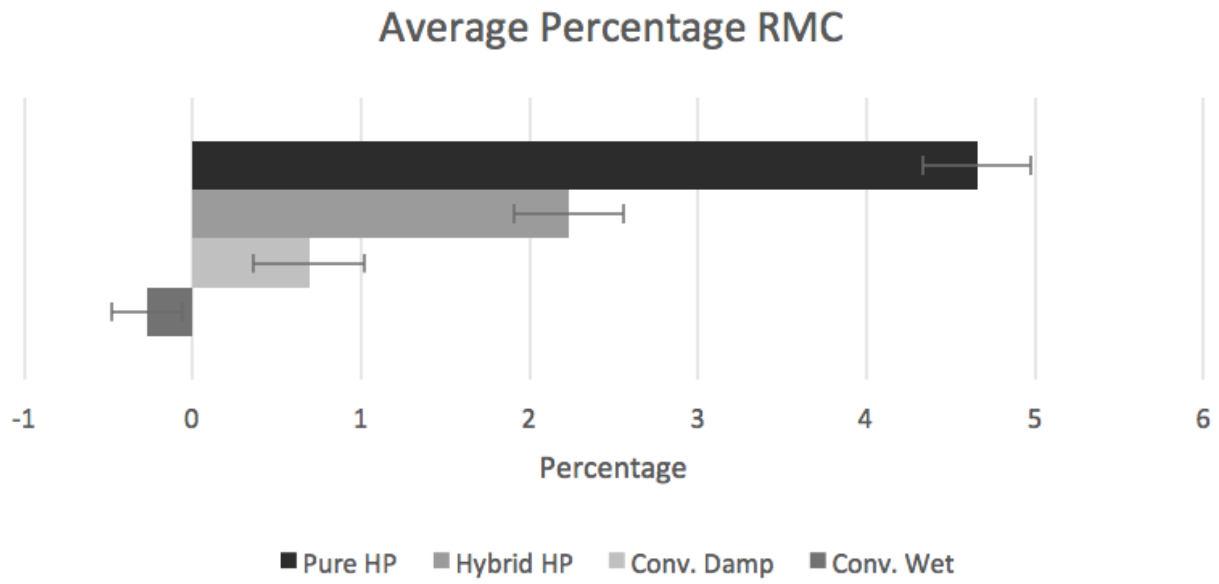
The drying time required for the Conventional Damp load was half as long as the other three loads in large part because the conventional wet load had significantly more moisture to remove (see Figure 3). This result shows that high spin speeds in washers reduces drying time when paired with conventional dryers, a point we will return to in the discussion.

Figure 3: Average Drying Times



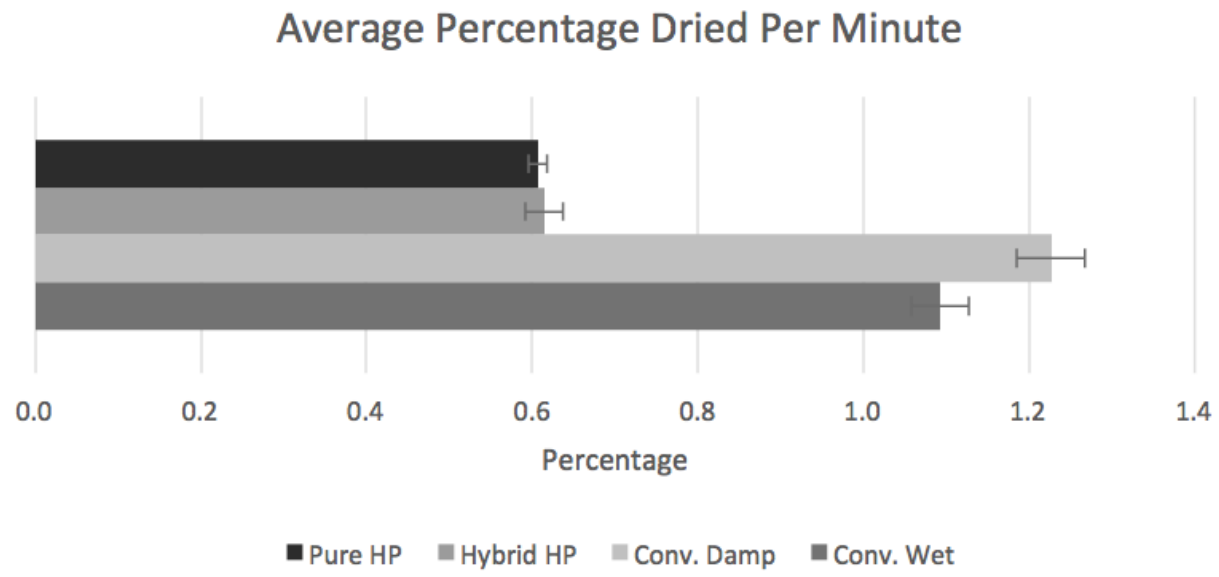
The Hybrid HP dryer also required slightly more time than the Pure HP dryer, and left the clothing with a lower moisture content (see Figure 4). However, the higher moisture content of the Pure HP load is close to the 3.3% moisture content that cotton typically exhibits at auto-termination, so this is a satisfactory result. The long drying time of the Conventional Wet load resulted in a very low RMC—low enough to cause concern that cellular-level damage could occur, as seen in previous studies of cotton fibers that are over-dried.[12]

Figure 4: Average RMC Percentages



These results do clarify that, for the purposes of this study, the Pure HP and the Conventional dryer represent opposing extremes in terms of temperature and dryness while the Hybrid HP represents a middle ground. The slightly longer average drying time of the Hybrid HP compared to the Pure HP disappears when the average percentage dried per minute is examined (see Figure 5). The conventional dryer removed moisture at a rate almost twice that of the heat pump dryers.

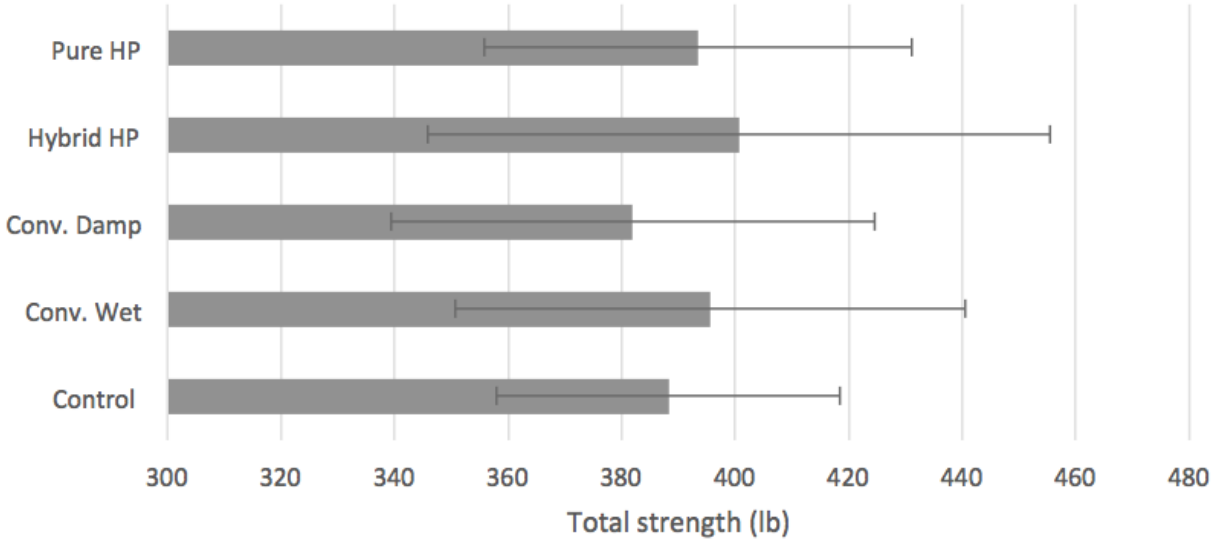
Figure 5: Average Percentage Dried per Minute



Fiber Strength

Overall, the fiber strength tests did not provide conclusive results. Figure 6 shows the total strength of each of the garments tested along with +/-2 standard deviations. Any differences are not statistically significant. Greater strength than the control could be explained by increased cohesiveness, which refers to the fibers bonding together due to heating.

Figure 6: Total Strength of Measured Garments in Each Load



However, there appear to be some correlations with specific garments. For instance, with the 100% cotton blue jeans (Jeans "A", **Figure 7**) shows a reduction in strength with increasing maximum fabric temperature in the dryer.

Figure 7: Cotton Blue Jeans Strength as a Function of Maximum Fabric Temperature in the Dryer

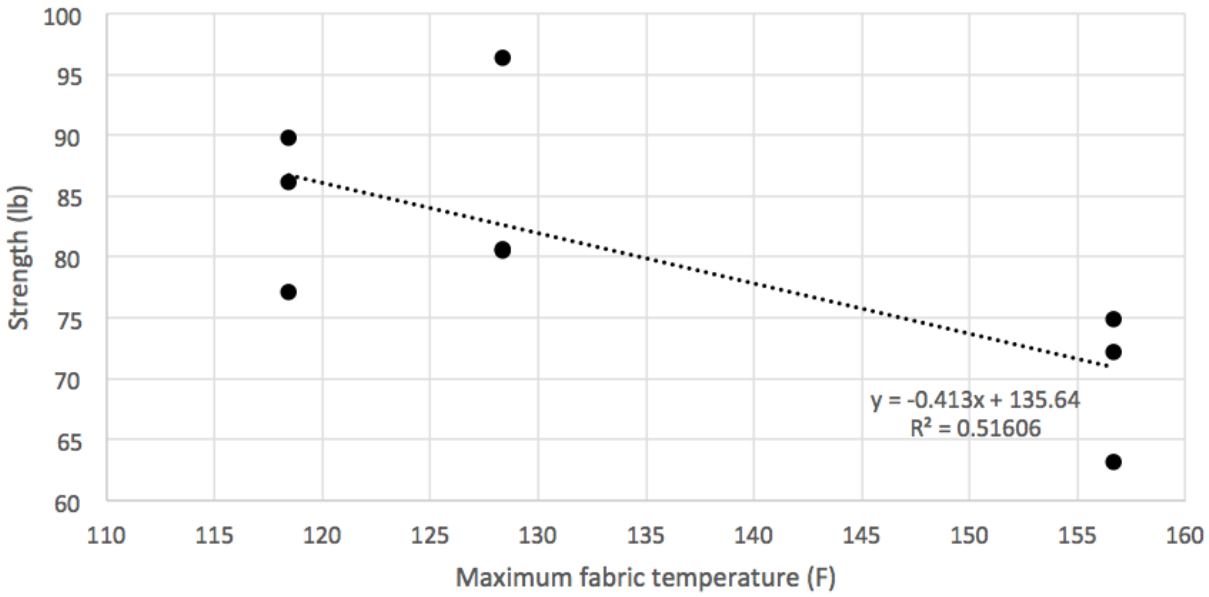
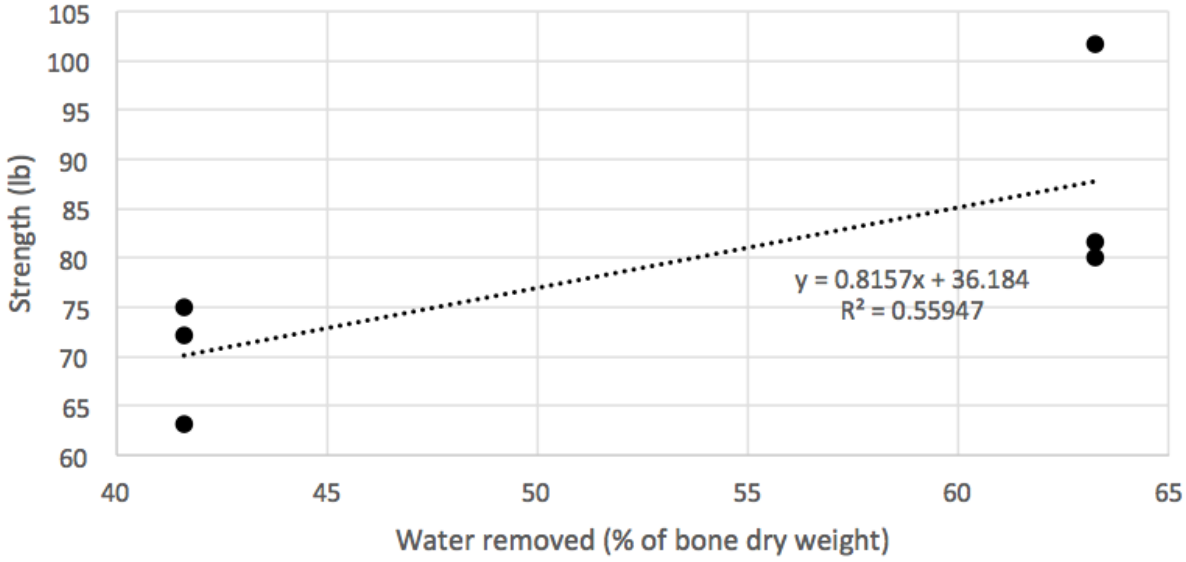


Figure 8 shows the strength of the same cotton blue jeans as a function of percent water removed with the conventional dryer. (Dryer temps were nearly the same in both of these cases.) This figure shows that jeans from the Conventional Wet load (that had to tumble longer) retained a higher fiber strength than jeans from the Conventional Damp load. Compared to Figure 7, the impact is less, thus it would appear any damage from higher spin speed is less than damage resulting from high temperature drying.

Figure 8: Cotton Blue Jeans Strength as a Function of Water Removed



However, the flannel pajama bottoms (Figure 9) and the half slip (Figure 10) show the opposite trend.

Figure 9: Flannel Pajama Bottoms Strength as a Function of Water Removed

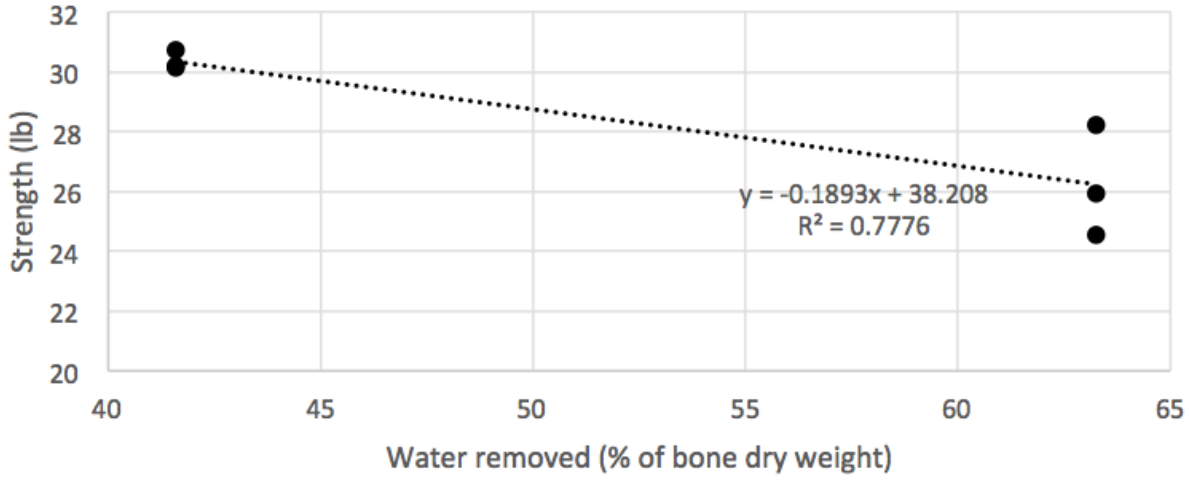
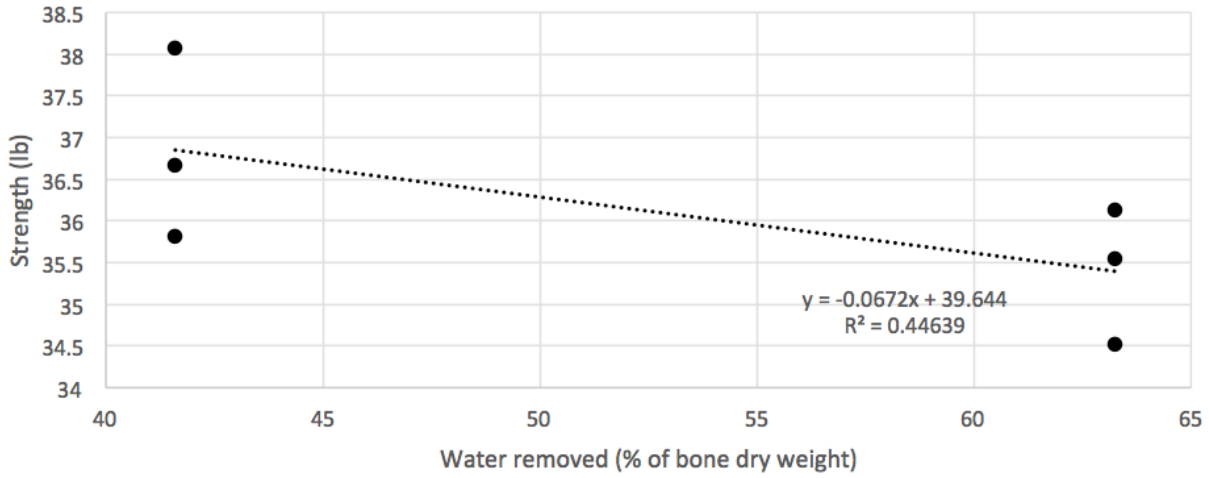


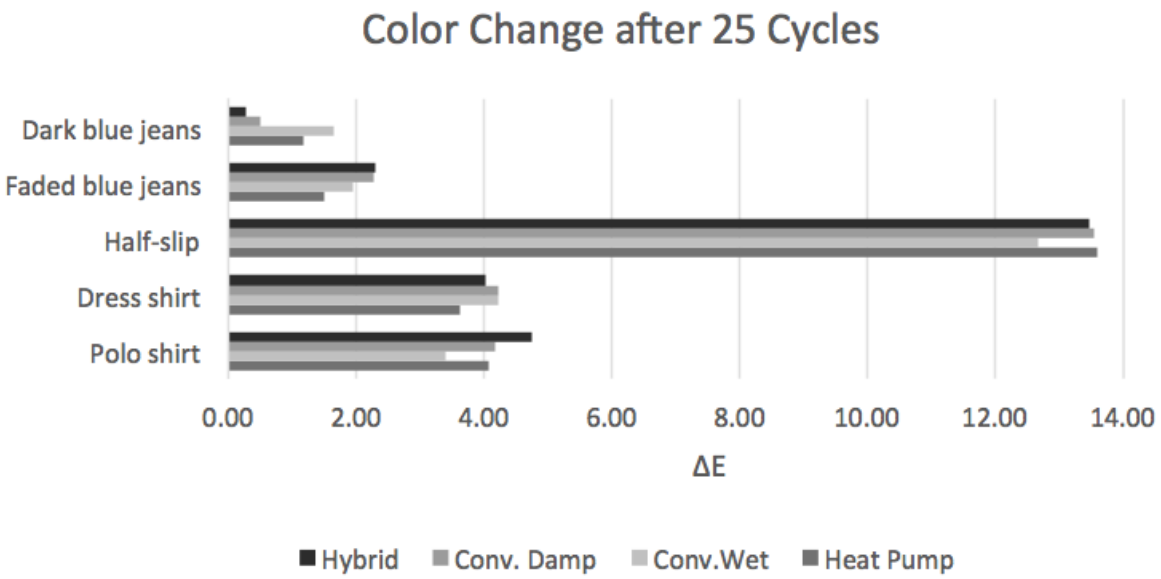
Figure 10: Half Slip Strength as a Function of Water Removed



Color

Our analysis of ΔE showed that no one particular dryer type has a greater impact on color loss than another type for most of the garments (see **Figure** Error! Reference source not found.**11**). The dark blue jeans (standard Levi's) did see some variation in color loss, and it is unsurprising that the nylon slip saw large ΔE, given that nylon is a "color scavenger" and would tend to pick up color from other items (likely the Levi's). However, this color change for the nylon half-slip and the jeans did not differ between load types by greater than ΔE =1, suggesting that consumers would be unlikely to notice any difference in color between the laundering methods.

Figure 11: Color Change for Selected Articles



Appearance

A textile professional performed a subjective evaluation of blinded photographs and was able to determine which garments had been subjected to all 25 cycles using each of the 4 methods, the evaluation did not provide conclusive evidence of increased or decreased wear for a particular dryer type. On average, the garments' scores decreased from 5 to 4 with the exception of the denim hems,

which began with considerable frosting (3 to 3.5) but did not increase in frosting over the course of 25 cycles. Based on this evaluation, consumers are unlikely to consider one drying method to be more damaging to their garments after 25 cycles.

Consumer Acceptance

The evaluation by consumers was done in two phases, with the five participants taking notes silently on each garment in the loads (which were randomly lettered) and then discussing the results as a group. A comparison of the notes and the discussion audio suggests that the opinions formed during the individual stage were not swayed highly by the group discussion. Every participant quickly noted the control load was "like new" and also that the nylon half-slip experienced the most dramatic color change.

When consumers were asked to rank the loads based on the acceptability of the results, 4 out of 5 participants gave the Hybrid load the highest score (second only to the Control load) and 4 out of 5 participants gave the pure heat pump load the lowest score (see Table 4). The one participant whose ranking diverged (she ranked the Conv. Wet and Conv. Damp as the top) admitted that she line-dries her clothing and prefers a "line dried feel" in her clothes. The participants preferred the Hybrid load for all of the clothing except the Levi's, which they found stiffer than they liked. They commented that the knit items had good elasticity and the acrylic sweater showed less pilling, less fiber loss and extended smoothly. One participant said, "I would like my clothes treated like S" (the code for the Hybrid load). In contrast, items in the Conv. Damp load (coded V) felt rough, the seams were puckered and waistbands twisted and there was agreement that the sweater and the lace on the slip were degraded the most. The denims in both conventional loads were softer, which the participants preferred, however later in discussion, participants expressed the most concern about the lifespan of their denims.

Table 4. Consumer Choices When Asked: Which Load is Most Preferable?

	Consumer #1	Consumer #2	Consumer #3	Consumer #4	Consumer #5
Top Pick	Control	Control	Control	Control	Control
#1 choice (after control)	Hybrid	Hybrid	Hybrid	Hybrid	Conv. Damp
#2 choice	Conv. Dry	Conv. Dry	Conv. Damp	Conv. Damp	Conv. Dry
#3 choice	Pure HP	Pure HP	Pure HP	Pure HP	Hybrid
#4 choice	Conv. Damp	Conv. Damp	Conv. Dry	Conv. Dry	Pure HP

We asked he consumer panel directly whether and to what extent their future dryer purchase decisions might be influenced by the knowledge that one machine could make their clothes last longer than another. The answer was a resounding and unanimous yes, but follow-up discussion revealed that the reasoning for this response had less to do with the cost of buying new clothes, and more to do with the preservation of favorite garments. This aspect of consumer behavior is a good subject for future study.

The consumer evaluation results suggest that the longer tumble time of the Hybrid and pure heat pump were not the source of noticeable degradation (confirming the photographic evaluation). It can be hypothesized that temperature had the greatest impact in degradation and consumer perception. High temperature may have increased approval for the softness of denim in the Conventional loads but may also be responsible for the pilling and damage to the more delicate items such as the slip and the sweater.

The implications for consumers of increasing energy efficiency in dryer methods can be evaluated using the results of this study. A series of objective tests found little to no difference between the methods in terms of wear and tear on a variety of garments with a variety of fiber types. The mixed loads created for the study were the "worst case" scenario in terms of combining weights and colors. If increased tumble time caused direct damage to delicate garments or abraded vulnerable edges, similar damage would have been seen in the "Conv. Wet" load to a greater extent than the "Conv. Damp" load—but this was not evident. The inclusion of both dark denim and nylon did create predicted bleeding and crocking; however, even with this strongly discouraged combination, there was no detectable difference between the dryer types. The conclusion can be drawn that consumers seeking energy savings and clothing durability do not need to be concerned that switching to a heat pump based technology will adversely affect clothing.

The study did demonstrate that the combination of high-speed extraction incorporated into washers as an energy efficiency measure (in the absence of highly efficient dryer technology) may have inadvertently accustomed consumers to a much shorter drying cycle. This lag between the improvement of washer and dryer efficiencies is unfortunate and it may take some education to help consumers understand that for dryers alone, previous research has demonstrated that "fast" means "hot" and that high temperatures are not friendly to their garments. This study also suggests that the "roughed up" appearance noted by the consumer panel in the Conventional Damp load is evidence of this increased damage compared with the wetter start in the same conventional dryer. Consumer education may be able to emphasize that replacing expensive garments—such as lingerie and denim—due to laundering damage represents an ongoing cost that may balance the longer time required to dry at lower temperatures.

Conclusions

We conducted this study to compare clothing wear between conventional electric resistance clothes dryers and heat-pump-based clothes dryers. By choice of equipment and load settings, the study also attempted to isolate and compare the effects of tumbling time and dryer temperature. (The study did not directly test other aspects of dryer efficiency, including the importance of accurate auto termination control, nor did it include the damage that occurs from actually wearing the clothing.) Our conclusions can be summarized as follows:

- Colorfastness testing and appearance evaluation using photographs gave no indication that clothing wear is accelerated or worsened by using a heat pump dryer.
- Tensile testing indicated that the cotton blue jeans maintained strength better by using a heat pump dryer. Other fabric types showed neither improvement nor worsening by using a heat pump dryer. Higher spin speed produced an inconclusive effect on wear.
- Consumers expressed a preference for garments dried with a hybrid heat pump dryer and there was slight preference against the pure heat pump dryer—although it did not consistently rank as the least preferred, and the consumers were generally satisfied with the amount of wear and tear for both dryer types.
- Consumer evaluation subjects clearly confirmed that the potential for reduced clothing wear could influence their laundry equipment purchasing decisions.
- Further testing may be required to determine if specific settings (e.g. delicate) that may appeal to consumers interested in preserving clothing life will also perform in a similar or superior manner with heat pump technology.

- High-speed extraction in washers reduces overall laundering energy use and time. Reduction in dryer cycle time is particularly important for heat pump dryers, though greater spin speed does mean lower energy savings potential for heat pump dryers.

Next Steps

This study suggests possibilities for future work in the area of dryer efficiency and clothing wear, as well as broader technology adoption strategies to help transform the American laundry market. These include:

- Compare ENERGY STAR and non-ENERGY STAR dryers to determine whether poor auto-termination results in increased clothing damage.
- Conduct further studies on the impact of initial moisture content on wear, which could help emphasize the importance of washer-dryer pairs, both in marketing and in field performance.
- Explore strategies for multi-family buildings, which have different purchasing and use profiles.
- Develop consumer-focused language that offers laundry "tips" such as bundling ENERGY STAR clothes washers with heat pump dryers to maximize customer benefits and savings potential.
- Investigate and quantify other possible non-energy benefits of heat pump dryers, including:
    - new construction benefits: first cost reduction from reduced or eliminated gas piping, venting, and exterior building penetrations, and
    - existing buildings benefits: possible maintenance cost reduction from ventless models, and possible reduced insurance costs.

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Appendices

Table 5. Load 1: Conventional Dryer Wet Start 25 cycles

Washer settings	Used for testing	Dryer Setting	Used for testing
Cycle	Quick Wash	**Cycle**	Normal
Wash Temp	Cold	**Temp**	Medium
Spin	Slow	**Dryness**	Normal
Soil	Light	**Wrinkle Shield**	Off
Extra Rinse	Off	**EcoBoost**	Off

Table 6. Load 2: Conventional Dryer Dry Start 25 cycles

Washer settings	Used for testing	Dryer Setting	Used for testing
Cycle	Quick Wash	**Cycle**	Normal
Wash Temp	Cold	**Temp**	Medium
Spin	High	**Dryness**	Normal
Soil	Light	**Wrinkle Shield**	Off
Extra Rinse	Off	**EcoBoost**	Off

Table 7. Load 3: Hybrid Dryer 25 cycles

Washer settings	Used for testing	Dryer Setting	Used for testing
Cycle	Quick Wash	**Cycle**	Normal
Wash Temp	Cold	**Temp**	Medium
Spin	High	**Dryness**	Normal
Soil	Light	**Wrinkle Shield**	Off
Extra Rinse	Off	**EcoMonitor**	Eco

Table 8. Load 4: Pure Heat Pump Dryer 25 cycles

Washer settings	Used for testing	Dryer Setting	Used for testing
Cycle	Quick Wash	**Cycle**	Cottons Regular Dry
Wash Temp	Cold	**Temp**	N/A
Spin	High	**Dryness**	N/A
Soil	Light		
Extra Rinse	Off		

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REPORT #E17-300

Addendum to Clothing Wear and Tear of Heat Pump vs. Electric Resistance Clothes Dryers

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Purpose

As a follow up to recent research for NEEA (*Clothing Wear and Tear of Heat Pump* vs. *Electric Resistance Clothes Dryers*), we tested one additional load that was significantly overdried. NEEA sponsored lab testing of conventional dryers shows that over-drying is common in conventional machines not designed to meet ENERGYSTAR performance levels. This extra test was to see if over-drying caused measureable damage to garments compared to the loads dried with heat-pump clothes dryers or conventionally dried with electric resistance dryers. This test also provided a side-by-side comparison between ENERGY STAR and non-ENERGY STAR drying methods, since the former includes automatic shutoff based on moisture sensing.

Methodology

In general, the testing process for this load was the same as for the five loads done in the main study; details are available in that report. Underwriter's Laboratories (UL) purchased two test loads (sets of garments) that were nearly identical to those used in the original study. Textile scientists selected the clothing to represent a range of fiber types and clothing designs, to provide data on fiber damage differences between different clothes dryer technologies.

The first load was used to experiment with different dryer settings to decide how to over-dry the clothes. These tests revealed that a typical cycle using the fabric test load achieved the target dryness of 4% in about 35 minutes. Earlier lab testing of various machines and clothing loads revealed that conventional clothes dryers dry clothing 15-20 minutes longer than necessary, with as much as 50 minutes longer than necessary in some machines and cycle settings.

The second set was then subjected to 25 cycles of washing and drying, with an additional thirty minutes of operation after achieving nominal dryness (<4% RMC). The final selection of settings was: 65-minute Timed Dry (with cool down period) at Medium temperature. This extended drying is equivalent to one to two years (40-50 cycles) of over-drying clothing that a typical conventional clothes dryer exposes clothing too.

For the overdried load, we conducted tensile testing, photography, microphotography, and hands-on evaluation. Spectrophotometry was inconclusive in the original study, so we did not test this load for color variations. It was not practical to reconvene the consumer acceptance panel that evaluated the first five loads, but a textile expert and several subjects provided opinions on the garments, including those from the overdried and original loads.

Results

Tensile Testing

The tensile testing results are shown in the series of graphs below. The first chart shows the total breaking strength for all garments in each load. The gray bar is the sum of the mean strengths for each garment, and the error bars represent ± 2 standard deviations. The following charts show the range and values of breaking force for the three samples of each garment tested.

Figure 1: Comparison of Total Tensile Strength from Each Load

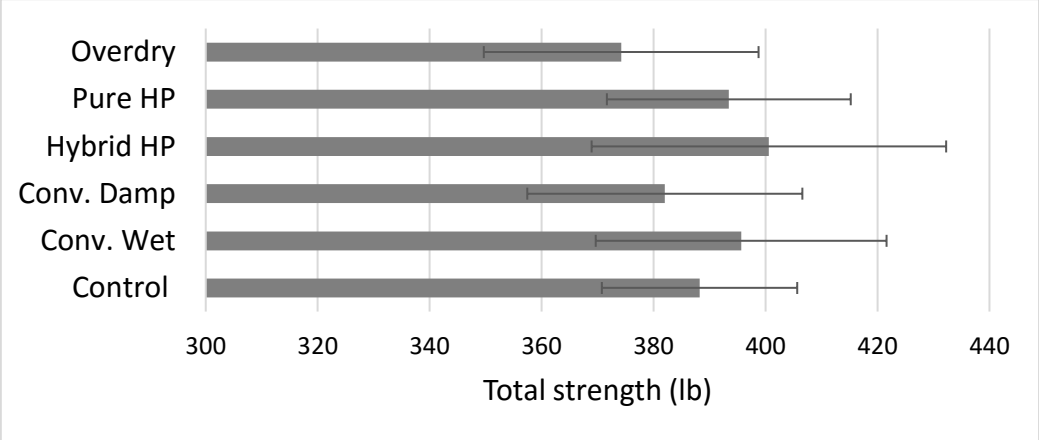


Figure 2: Tensile Strength of Levi's Jeans

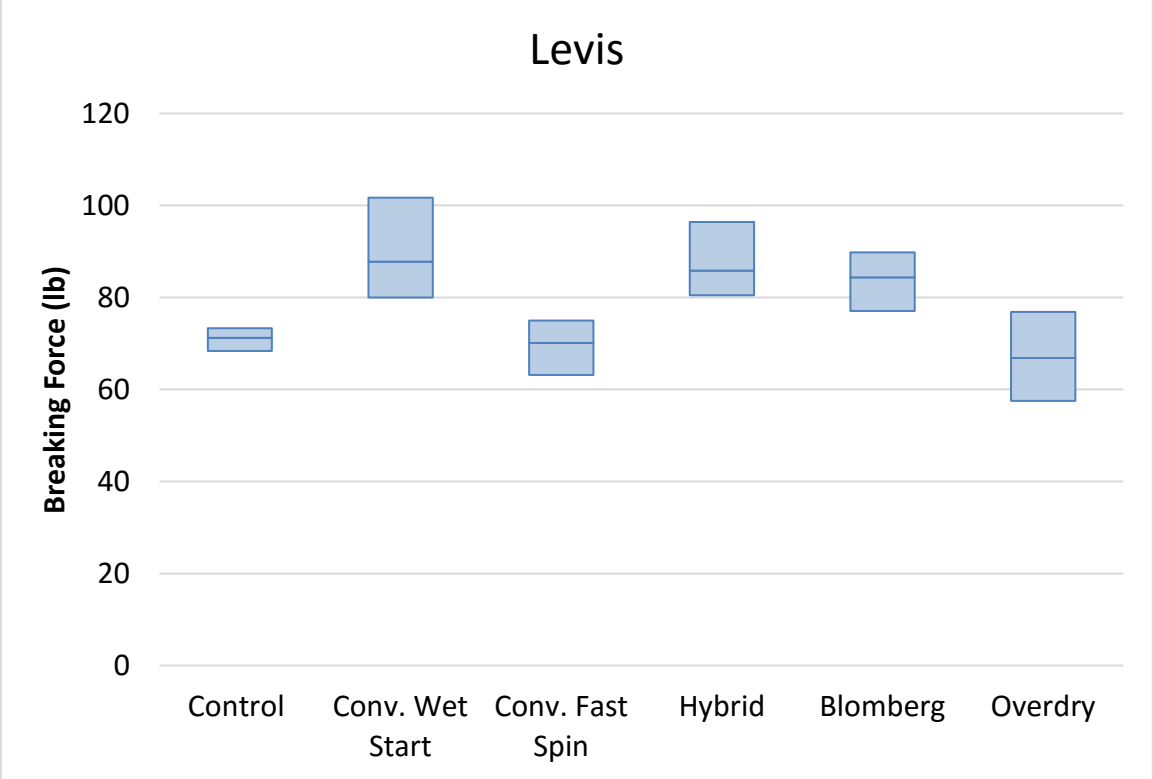


Figure 3: Tensile Strength of Old Navy Jeans

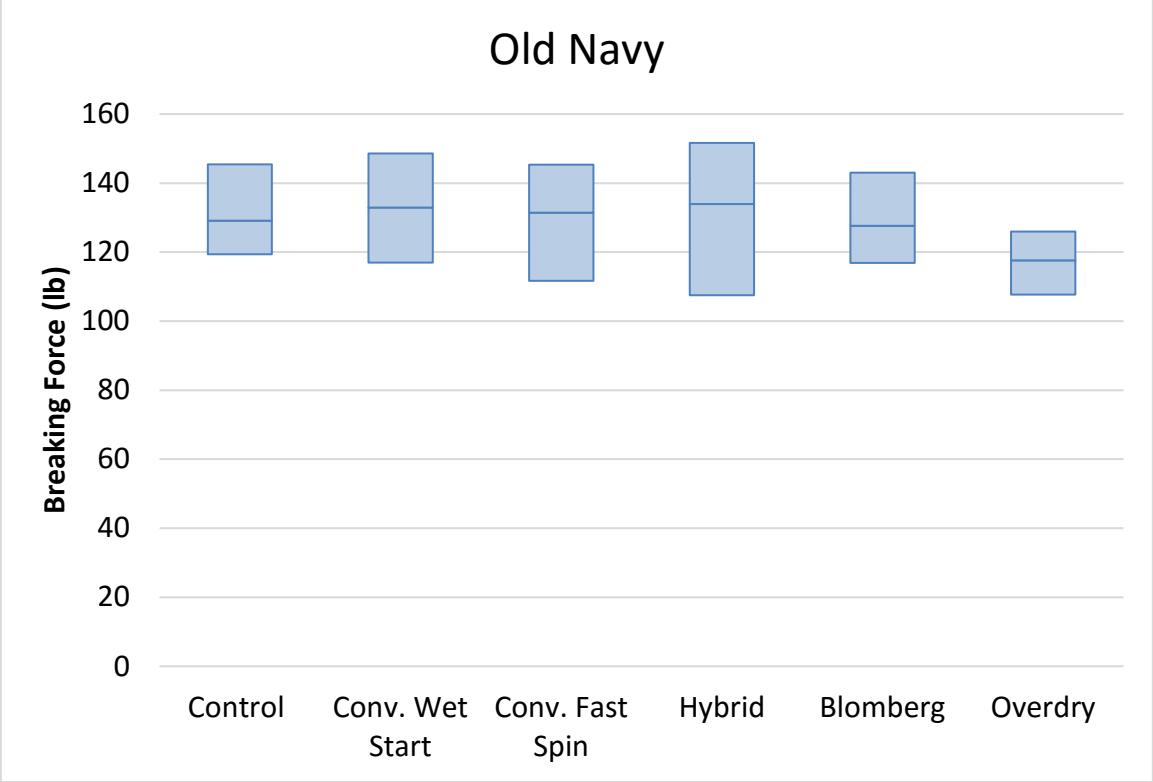


Figure 4: Tensile Strength of Work Shirt

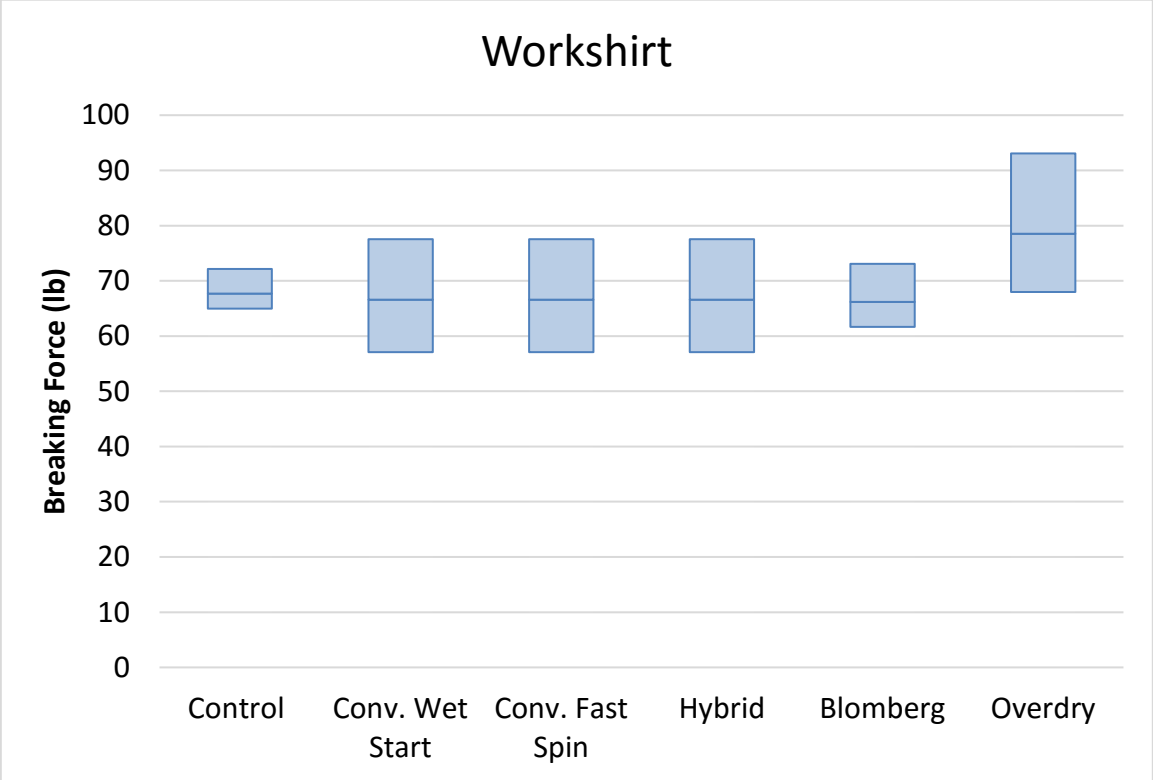


Figure 5: Tensile Strength of Dress Shirt

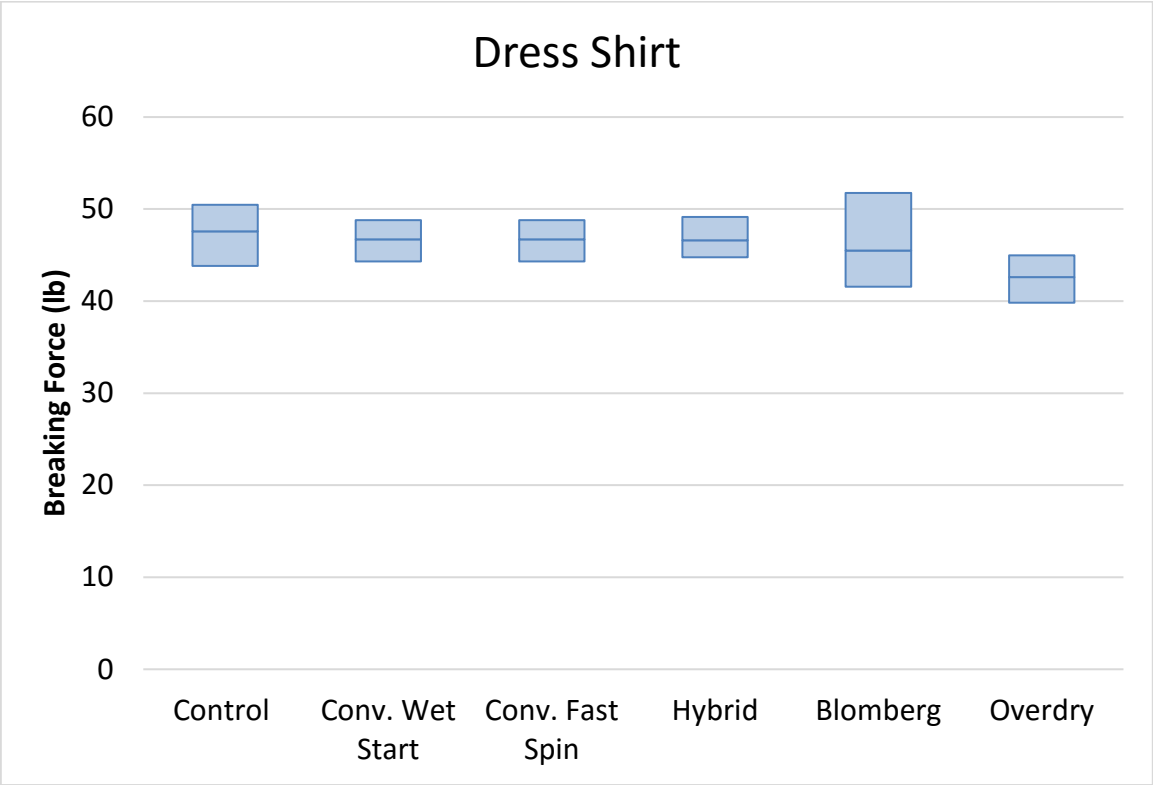


Figure 6: Tensile Strength of Flannel PJ's

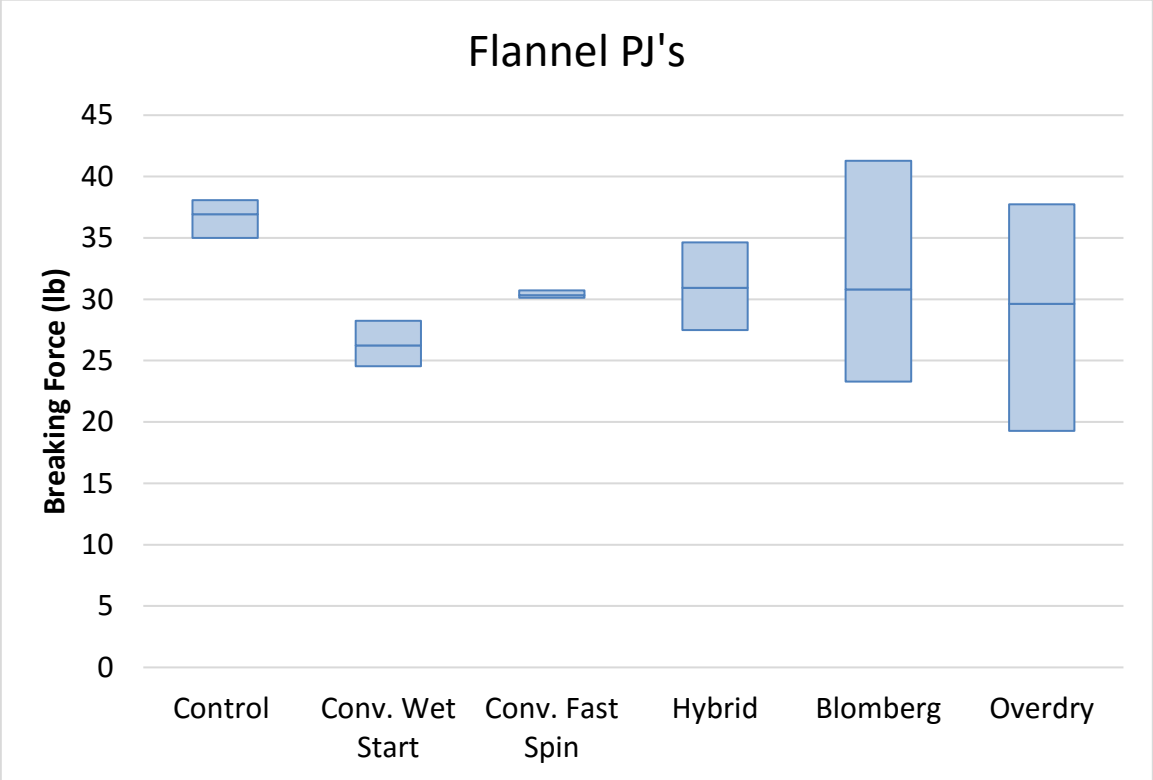
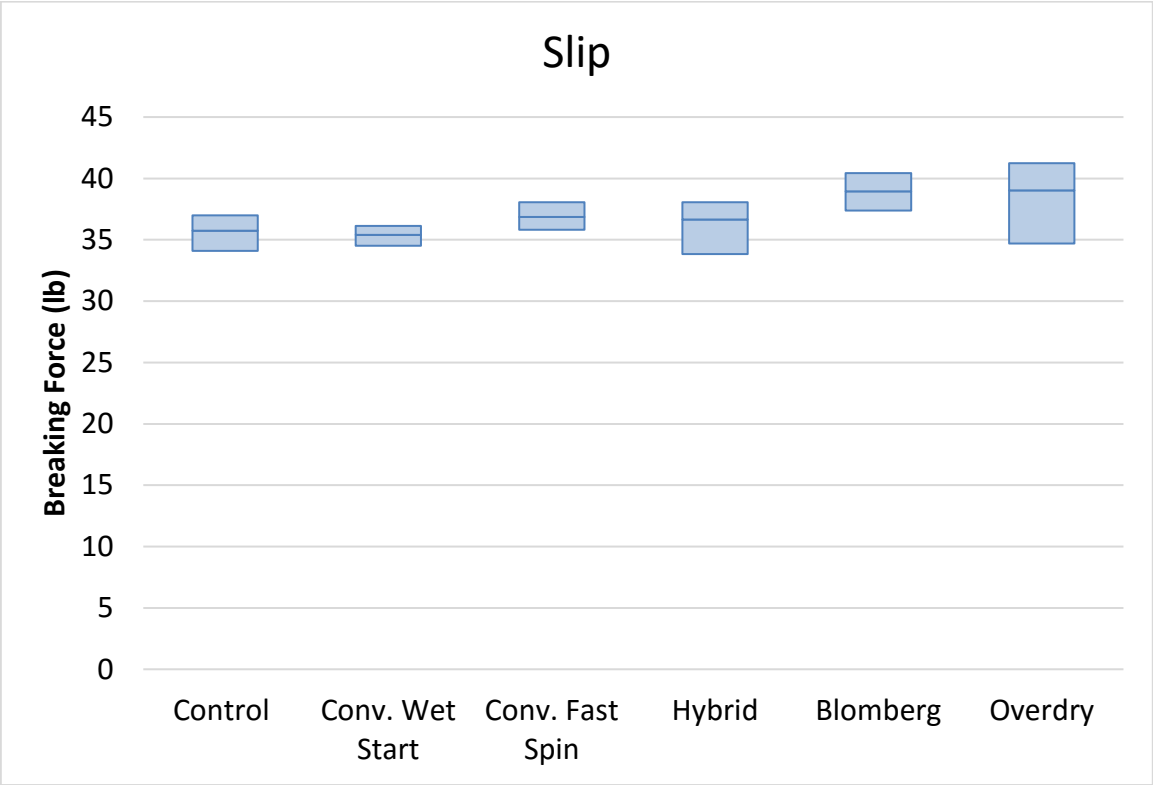


Figure 7: Tensile Strength of Slip



Although both types of jeans showed slightly lower tensile strength in the overdried loads, the workshirt and slip showed slightly higher tensile strength. Overall, the tensile testing results are inconclusive.

Photography

In the original study, a series of photographs documented specific parts of each garment from each load. A textile expert then evaluated the photos to look for differences in wear, as well as factors such as pilling, frosting, and color change. With the overdried load, UL photographed the garments as before; a sample of these photos is shown below. However, because the actual garments went to the textile expert for evaluation as described below, notes on these textile factors are based on the physical comparison rather than the photographs.

Figure 8: Sample Photographs of Overdried Garments

Polo Shirt

Dress shirt

Jeans (upper)

Jeans (lower)

Microphotography

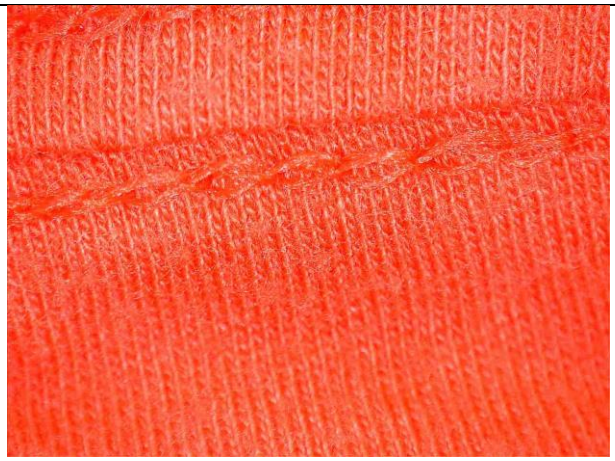
We took 80x micro-photographs of selected garments. These photographs did not show excessive wear compared to the conventionally-dried garments in the original study (i.e. non-overdried). Sample micro-photographs are shown in the figure below.

Figure 8: Sample Micro-Photographs of Overdried Garments

Pajamas at front elastic

Polo shirt at right sleeve hem

Sweater at bottom left hem



T-shirt at right hem

Expert Evaluation

A textile scientist and four other persons trained in objective evaluation techniques for apparel conducted a blind evaluation of the loads of clothing, including the overdried load. The evaluation considered each item for properties such as: pilling, stiffness, smoothness of surface/seams, and color change. The evaluation used a 1-5 scale, typical for evaluation of apparel, with 1 being the most negative level of the property, 5 being the most positive level of the property and 4 being the level of the property that is acceptable to the average consumer.

The blind evaluation identified the control loads immediately as they were consistently rated as 5s on each property. The remaining loads each had items that were better rated than others. No load was consistently higher rated than another, confirming the results of the consumer panel, the microscopy and the tensile testing. The loads dried with higher levels of heat in the conventional dryer (after both fast and slow extraction cycles in the washing machine) had lower ratings for stiffness and surface/seam smoothness but higher ratings for pilling. The loads dried at lower temperature (but with longer tumble times) showed slightly more evidence of roughening of the yarns from abrasion, although no outright pilling, even after 25 cycles. Neither load received ratings lower than 4 except for color change on the nylon slip, which is prone to this issue and had color transfer in all of the loads.

This evaluation attempted to compare the performance of the elastic elements in some of the garments. This is normally done by measuring before-and-after elongation, or by calculating a modulus of elasticity from tensile testing. Because the focus of this study was on consumer acceptance, the group evaluated elasticity by handling the garments. They found no significant differences between the loads. Furthermore, the evaluators found none of the signs—such as smells and sounds—that typically indicate incipient elastic failure.

The main conclusion from this evaluation confirmed that a realistic, mixed load of apparel demonstrates that energy efficient dryers do not damage apparel or reduce the lifetime performance of the apparel to any degree higher than conventional dryers. Just as consumers have grown accustomed to (or prefer) the stiffness and subtle surface changes that results from drying at high heat, other consumers appreciate the softer "hand" of the low-heat dryers. These mixed loads, while more realistic than dummy fabrics, are not necessarily reflective of the habits of careful consumers, who might not put a knit sweater and a white nylon slip in the same load as two pairs of blue jeans. The results of this study using a "worst case" scenario of a load with multiple types of fabrics and fibers should be reassuring to dryer manufacturers and consumers alike that energy efficient dryers show no indications of reduced garments lifetimes.

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