An Intelligent Washing Machine for the Evaluation of Laundry Detergents[1]

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ABSTRACT

A computer-controlled washer can be programmed to evaluate automatically a large number of washing compositions for soil removal. Variable amounts of as many as six different detergent components are added with metering pumps. A continuous roll of soiled cloth passes through a washer and past a reflectance meter onto a take-up reel. Washing action is provided by a vertical reciprocating shaft attached to a plate which rubs on the fabric while tension is maintained by a spring-loaded roller. The length of the wash, number of rinses and addition of components is controlled by the computer program. Upon completion of the wash and rinse cycle, the fabric is advanced about 10 cm. Washed areas appear as lighter colored bands on the fabric. In one mode of operation a large factorial experiment is programmed in advance. After an initial calibration of metering pumps the apparatus runs unattended. In another mode, the computer receives feedback from the reflectance meter and a simplex procedure is used to determine the direction of maximum cleaning. Following the execution of a small number of initially programmed washes, the computer selects the succeeding wash compositions.

INTRODUCTION

The laboratory evaluation of laundry detergents in a Terg-o-tometer (1) requires nearly continuous attention of an operator for the following tasks: measurement of make-up wash water and separate detergent components for each wash; identification and addition of test swatches to each wash bucket; recovery of washed swatches upon completion of the wash; drying and sorting of washed swatches; recording of instrumental reflectance values; and statistical analysis of recorded data.

This paper describes a computer-controlled apparatus which carries out the equivalent of these operations without further operator attention beyond an initial data input and calibration. Primarily we have felt the need to automate the test procedure in order to carry out the large number of experimental trials required adequately to explore the effects of both composition changes and use conditions. If mechanical and electrical malfunctions can be eliminated, there should be a substantial gain in the reliability of the detergency data obtained by the apparatus. In the usual Terg-o-tometer procedure there are many possibilities for error, such as a mistake in the amount of an added component or misplacement of a test swatch.

AUTOMATED WASH APPARATUS

Soiled Fabric

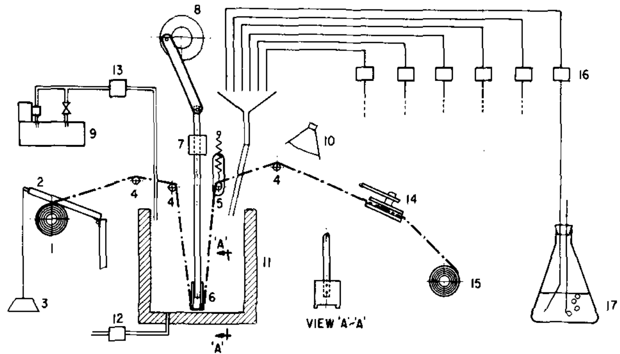
The experimental results in this paper were obtained with a roll of 50/50 polyester/cotton blend (Fabric No. 7428 from Test Fabrics, Inc., 200 Blackford Avenue, Middlesex, NJ) which had been soiled with liquid make-up ("Summer Bronze" from Helena Rubenstein). The soil was applied directly with a padder (Model KLFA/k) and dryer (Model KTF/m) made by Ernst Benz Co., Zurich, Switzerland, with a method developed by C.A. Beagle in our Laundry Evaluation Section. The soiled fabric had ten reflectance values within the range of 28.3–29.0% along its length. In factorial experiments, we were protected from any systematic error along the length of the fabric by using a random order of experimental trials.

Increase in the spring tension which holds the fabric against the wash frame increased soil removal and produced noticeable abrasion of the fabric in a prolonged wash. However, under the conditions described here, there is no visually apparent abrasion of the cloth. In a limited number of other experiments in which both automatic washer and Terg-o-tometer wash results were obtained on the same wash solutions, good correlation between the two sets of data was obtained. Departures of plotted values from linearity did not exceed the expected distribution due to replication error.

Wash Operation

A schematic diagram of our apparatus is shown in Figure 1. A continuous roll of soiled fabric, 6 cm wide, leads from the feed spool into the wash vessel past the bottom of a square frame attached to the agitator shaft. A side view of the agitator assembly is also shown. The shaft has a vertical oscillatory motion over a distance of 5 cm and is driven at 120 cycles/min. An upward tension of ca. 400 g is maintained on the fabric by a roller bearing attached to springs at each end. Ideally, the same mechanical action is applied to each washed section of fabric rather than the random action which occurs when the soiled swatch floats freely in the wash bath. If the mechanical washing action is uniform from wash to wash, the reproducibility of the cleaning should be largely determined by the uniformity of the fabric and the applied soil.

The wash vessel is a one-liter stainless steel beaker surrounded by a temperature-controlled water jacket. At the



1. FEED SPOOL
2. BRAKE ARM
3. WEIGHT
4. ROLLER BEARINGS
5. SPRING LOADED TENSION ROLLER
6. SQUARE FRAME ON WASH SHAFT (VIEW 'A'-'A')
7. NEEDLE BEARING
8. RECIPROCAL DRIVE, 120 CYCLES PER MIN.
9. CONTROLLED TEMP. WATER BATH
10. HEAT LAMP
11. JACKETED WASH BATH
12. SOLENOID DRAIN VALVE
13. SOLENOID VALVE FOR WASH WATER FILL
14. BACKING PLATE AND REFLECTANCE METER
15. MOTOR DRIVEN TAKE-UP SPOOL
16. SOLENOID METERING PUMPS
17. CONSTANT HEAD COMPONENT RESERVOIRS

FIG. 1. Schematic diagram of automated wash apparatus.

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start of a wash cycle, a solenoid valve opens to allow make-up water to flow from a circulating water line in a temperature-controlled reservoir at ca. 500 mL/min. The make-up reservoir holds 15 L and is refilled automatically. Programmed amounts of up to 6 components are added with separate solenoid metering pumps (Model SV-500, Valcor Engineering Corp., Kenilworth, NJ) to provide 600 mL wash solution. To avoid a change in pumping rate caused by a difference in liquid head, component solutions are stored in Mariotte flasks. The concentration of stock solutions is usually adjusted to provide for additions in the range of 0–20 mL with a standard error of ±0.1 mL in the programmed delivery. An obvious limitation is the requirement that the components be in a pumpable form, generally an aqueous solution. We have been able to add certain components in the form of easily dispersable emulsions or particulate systems by adding a stirring bar to the reservoir.

The agitator is turned on for a programmed time interval. There is a more intense washing action on the section of fabric in continuous contact with the agitator blade than there is on an unconstrained test swatch. With EMPA 101 test fabric, ca. 2½ min of washing is sufficient to obtain the same soil removal as a 10-min wash in a Terg-o-tometer. The 90° angle at the bottom of the wash frame ensures flexing of the fabric for increased soil removal. (In our initial design the fabric strip passed under a 1-cm diameter roller bearing at the bottom of the wash frame and very little soil was removed.) The solenoid drain valve opens for 25 sec when the wash is complete.

Fabric Advance

Upon completion of the final rinse, the motor drive on the take-up spool is turned on for a programmed interval. The advance is adjusted in order that the photodetector will scan one washed area from a previous cycle. This distance is either 2/5 or 2/7 times the 40 cm of cloth separating the center of the washed area under the agitator and the photocell. The longer advance avoids possible interactions between successive washes by providing an unwetted area between washed sections of fabric. The number of turns, T, of the take-up spool required to advance the fabric a distance, d, is programmed into the computer by the following expression:

$$T = d/(2\pi(R_0{}^2 + \pi ndt)^{1/2})$$

where R_0 is the initial spool radius, t is the thickness of one layer of fabric, and n is the number of wash cycles completed.

The take-up spool turns at a nearly constant rate which is programmed into the computer after an initial calibration. The computer records 20 readings from the photocell at equally spaced intervals during the fabric advance. The mean of the 3 highest readings is recorded as the detergency value of a washed area. The computer also records the position at which the maximum reading was obtained and, if necessary, makes a small correction (±5%) in the turning rate constant to maintain the correct fabric advance. A heat lamp is adjusted to ensure that the fabric is dry by the time it reaches the photocell. The combined light source and photocell (Model S-1 Darlington Scanner Assembly, Scanning Devices Inc., Waltham, MA) is installed inside a 2 cm id metal tube 2 cm above the fabric surface where it passes over a flat neutral gray backing plate. The measured response is not the same as a visual reflectance value since the photocell has maximum response at 870 nm. However, we have found an essentially linear relationship between detector readings and visual R_d values for the limited range of readings required to span different levels of soil removal for a particular soiled fabric.

Computer I/O

An interface to a Model I Radio Shack Computer provides 10 logic outputs to control relays for 6 component addition pumps, a solenoid drain valve, a wash-water addition valve, an agitator motor and a fabric advance drive motor. There is also digital input from a 12-bit A/D converter connected to the photocell. Output and input ports are directly addressable from a basic language program.

Experimental Procedure

The delivery volume of each wash component for each wash cycle is initially entered as data lines at the keyboard or loaded from a casette recorder. A printed record of each wash is also obtained. At the start of the program the make-up water delivery tube is changed from the washer to a 1-L graduate to check the delivery rate as follows. (a) The make-up water fill valve opens for an interval, T, and the delivery, V, is measured (600 mL required). (b) V is entered at the keyboard and the computer adjusts T by a factor 600/V. (c) Computer requests input either to recheck calibration or to continue.

A similar routine is then used to check the 6 component metering pumps. These have been adjusted to deliver ca. 0.1 mL per stroke at a pumping rate of 120 strokes/min and the number of strokes required to deliver 10 mL is determined. When calibration is completed the program proceeds automatically as follows: make-up water and programmed amounts of other components (600 mL total) are delivered to the washer; the agitator is turned on for the programmed wash time; contents of the washer are drained, followed by 2 rinses with make-up water; and fabric advances for the next wash cycle and the reflectance of a previous wash is recorded as previously described.

About 4 washes an hour are completed with a 5-min wash time and 2 rinses.

EXPERIMENTAL RESULTS

Central Composite Rotatable Design

Coded levels for a design with 5 independent variables (2) are shown in Table I.

The design includes an initial 16 points which form a balanced half-replicate of a 2^5 factorial design in which the coded level of each variable is held at ±1. In addition, there are 10 points in which each variable is at a ±2 level while the rest are at their center point values. An estimate of experimental error is provided by six replicate points at the

TABLE I

Percent Wash Concentration × 100

Component	Coded levels −2	−1	0	1	2
X1, LAS[a]	2	3	4	5	6
X2, Neodol 23–6.5[b]	0.4	0.6	0.8	1.0	1.2
X3, Na_2CO_3	2	3	4	5	6
X4, $Na_5P_3O_{10}$[c]	2	3	4	5	6
X5, Na_2SO_4	2	3	4	5	6

[a] Sodium salt of linear tridecylbenzene sulfonate.

[b] Ethoxylated fatty alcohol obtained from Shell Development Company.

[c] Sodium tripolyphosphate.

center of the design. The fitted model for the design is a complete quadratic expression in coded units

$$\hat{y} = b_0 + \sum_{i=1}^{5} b_i x_i + \sum_{i=1}^{5} b_{ii} x_i^2 + \sum_{i<j} b_{ij} x_{ij}$$

where $\hat{y}$ is the estimated detergency response at a point determined by the component variables and the b values are fitted coefficients.

The analysis of variance in Table II shows considerable significance for the linear first-order terms (F = 49.3). There is no significant lack of fit and the model is a good predictor of detergency within the experimental range covered. Table III lists coefficients in descending order of significance for a t statistic based on the standard error of the fitted coefficient.

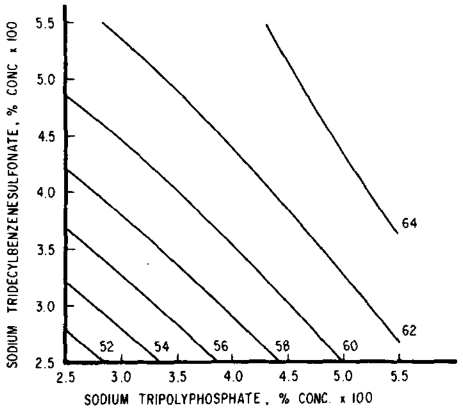

FIG. 2. Reflectance contours.

TABLE II

Analysis of Variance

Source	DF	SS	MS	F
First-order terms	5	295.1	59.03	49.3
Second-order terms	15	44.9	2.99	2.5
Lack of fit	6	3.7	0.62	0.5
Pure error	5	5.9	1.19	
	31	349.6		

TABLE III

Term	Coefficient	t Statistic
$Na_5P_3O_{10}$	2.40	10.8
LAS	2.38	10.7
Na_2CO_3	0.90	4.0
$Na_5P_3O_{10} \times Na_2CO_3$	−1.03	3.8
$Na_5P_3O_{10}$ × LAS	−0.84	3.1
LAS × LAS	−0.53	2.6

Constant term, $b_0 = 61.2$.

There are 14 other terms in the complete equation but they are all small and not statistically significant. Most of the change in response is from the simple linear effects of the phosphate builder and anionic surfactant. This is shown by a contour plot, Figure 2, in which other variables remain constant at their center point values. The entire experiment including statistical analysis of the data was accomplished within an 8-hr period.

Simplex Design

A computer-controlled apparatus is well suited to the determination of conditions for optimum detergency by an approach in which the selection of a current experimental trial is determined by past performance. In the simplex method as proposed by Spendley et al. (3), k + 1 initial experimental points are the corners of a simplex in k-dimensional space with axes representing k independent variables. A more recent review of the simplex method is by Deming and Parker (4).

Initially, the response values are determined for the k + 1 points of the simplex. In the original algorithm the next experimental point was obtained by discarding the initial point with the lowest response and replacing it with a new point on the opposite side of the simplex. In the case of the automated washer we did not have response values for all of the initial simplex points in an experiment with 5 variables at the time when a decision on a new point was required as only the first 3 of the initial 6 washes had been scanned by the photocell. In this case the lowest of the first 3 response values was eliminated. It does not appear that this lag seriously interferes with the efficiency of the simplex procedure. The coordinates of a new simplex vertex, V*, were computed with the formula:

$$v_j^* = \frac{2}{k}\left(\sum_{i=1,\, i\neq j}^{k+1} v_i\right) - v_j$$

where v_j^* is a coordinate of a new vertex, v_j is the corresponding coordinate of the vertex to be eliminated and v_i is a corresponding coordinate of a remaining vertex. The computer was also programmed to repeat any simplex point which had survived for more than k + 4 washes and to replace the old response value with the newly determined one to provide protection against a spuriously high value. It was also possible for the algorithm to calculate a negative value for a component to be added. In this case the negative value was retained by the computer memory but the effective result was 0 addition of that component. Using the same component variables as in the previous example, the initial 6 washes were programmed with the wash concentrations shown in Table IV along with the photometer readings recorded by the computer.

Figure 3 is a plot of the readings for the initially programmed washes (up to the vertical dashed line) and the subsequent readings for wash compositions determined by the simplex program in the computer. There is an initial rapid rise in reflectance followed by a slowly rising plateau. The photometer reading, P, recorded by the computer can be used to calculate a visual percentage reflectance value, R, by the regression equation:

$$R = 9.25 + 0.102P$$

The cumulative composition of the wash solutions in Figure 3 is shown in Figure 4. Neither the nonionic surfactant or sodium sulfate affect detergency under the conditions used in this experiment, whereas the anionic surfactant, phosphate builder and sodium carbonate are all increased over the initially programmed amounts.

TABLE IV

Initial Simplex Wash Compositions

	% Wash concentration X 100					
Wash no.	1	2	3	4	5	6
LAS	2.0	3.8	2.4	2.4	2.4	2.4
Neodol 23–6.5	0.40	0.48	0.76	0.48	0.48	0.48
Na_2CO_3	2.0	2.4	2.4	3.8	2.4	2.4
$Na_5P_3O_{10}$	2.0	2.4	2.4	2.4	3.8	2.4
Na_2SO_4	2.0	2.4	2.4	2.4	2.4	3.8

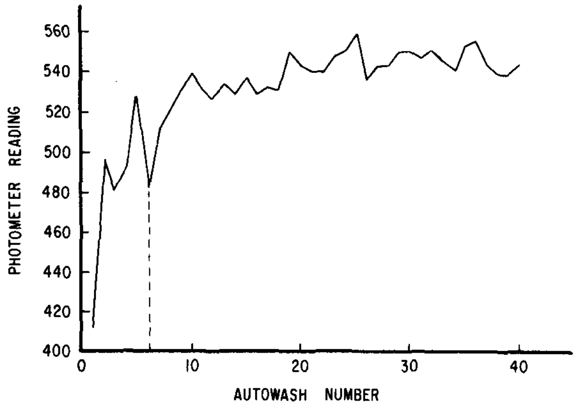

FIG. 3. Simplex optimization.

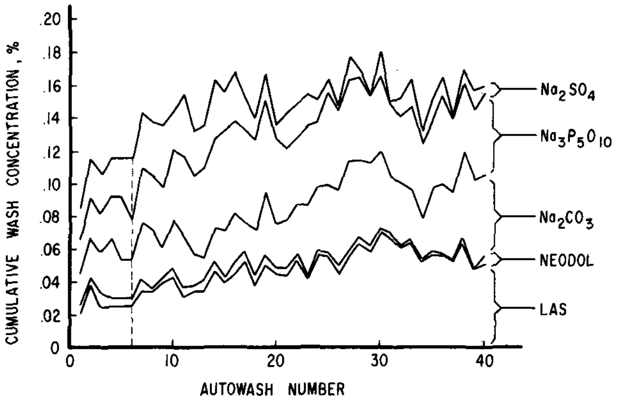

FIG. 4. Simplex optimization.

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L. Hernandez contributed to the mechanical design and construction of the apparatus. The computer interface was designed by C.W. Gregory.

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