HORIZONTAL AXIS DOMESTIC CLOTHES WASHERS: AN ALTERNATIVE TECHNOLOGY THAT CAN REDUCE RESIDENTIAL ENERGY AND WATER USE

Benoit Lebot, Isaac Turiel, and Gregory Rosenquist
Lawrence Berkeley Laboratory

This paper presents the significant potential for energy savings by a clothes washer with technology that is barely known and used in the United States. Incorrectly named "front-loading" clothes washers (as opposed to top loading machines), these residential washers have a horizontal axis tub that tumbles the clothes. Because of this design, they consume much less energy and water than a conventional vertical-axis washing machine. In 1990, DOE will promulgate, for the first time, standards for dishwashers, clothes washers and clothes dryers. It was found that even the most advanced design for conventional washers saved only a small fraction of the potential savings from switching to horizontal axis machines.

A clear description of the alternative washing process is given. Emphasis is placed on the use of energy and water. Data for energy use and efficiency have been collected from manufacturers of horizontal axis machines. A new definition of energy efficiency is proposed and used to emphasize the pronounced differences between the two washing technologies. Actual data on existing machines illustrate the achievable savings and are used to calculate payback periods for substituting one technology for another.

Finally, since horizontal-axis washing machines have the best potential with regards to not only energy conservation but also for water reduction opportunities, this paper reviews advanced design features on existing and new machines which would save even more energy and water.

INTRODUCTION

Two different technologies have been developed for the process of washing clothes automatically. The first one consists of a tub standing on a vertical axis that is equipped with an agitator rotating on this axis. The second process involves a cylinder rotating on a horizontal axis that tumbles the clothes. Market shares of the latter account for less than 5% in the United States but as much as 95% in Europe. Because of their specific design, the two technologies have different mechanical actions requiring different hot and cold water usages. Data obtained from manufacturers of both types of machines allow comparisons of energy and water usage. An economic analysis allows us to evaluate the energy and dollars savings of the horizontal axis technology compared to the vertical-axis machine. It was found that existing horizontal-axis machines are not only cost effective, but further design options can be applied to make them even more energy efficient.

THE PROCESSES OF WASHING CLOTHES

Concept of Clothes Washing

Washing clothes is the process of removing very small amounts of soil from the fibers of a garment. This can be achieved in a water medium through a mechanical action, a chemical action or through a combination of the two. A mechanical action forces the soil to leave the clothes fibers. Soils are evacuated through the water. Mechanical action is usually produced by moving a piece of clothing over a non-soft surface or by moving the individual pieces of clothing over one another. Ultrasounds are also said to produce the necessary mechanical action to extract the soil from clothing. A chemical action is achieved by adding some oxidizers and other chemicals to the water. Oxygen, derived from decomposition of oxidizers into the water reacts with the insoluble organic compounds (the dirt). Together they form a soluble organic compound which becomes dislodged from the clothes. Temperature is the main catalyst for the reaction of the organic compound and the chemicals contained in the detergent.

Technological Answers to Clothes Washing

Two different processes have been adopted by the clothes washer industry to achieve both the chemical and mechanical actions for clothes washing. The first process consists of a fixed cylindrical tub standing on a vertical axis where an agitator forces the load to move in a water-detergent solution. The agitator, designed with some vertical paddles, is the same height as the tub and is located on the cylinder's main axis. Clothes are loaded from the top of the tub. This is the typical American clothes washer which accounts for more than 95% of the US market. Reasons for the high penetration of this type of clothes washer are not known to the authors.

The second process involves a cylinder rotating on a horizontal axis and which tumbles the wash load. Clothes are usually loaded from the axis direction of the drum which has led this type of machine to be called a Front-Loader. These clothes washers largely dominate the European market.

An automatic clothes washer, with either a vertical or a horizontal axis, usually follows this wash cycle: The tub is filled with water that is heated to the selected temperature. The motion of the agitator or the tumbling of the drum causes a turbulent environment, which provides friction between the load, the tub and the agitator. After wash and rinse periods, the water is drained and the basket begins to spin, creating centrifugal forces which remove more water from the load.

Wrong Terminology

Before proceeding, we must clarify how the two types of washers are classified. The European-like clothes washer, with its tub rotating on its horizontal axis, is commonly termed a *Front Loader* as opposed to a *Top Loader* (the American-like, vertical-agitator clothes washer). It is true that many horizontal axis washers are front loading, but they can also be top loading as well. In that case, the drum has a door that can slide or rotate (see Figure 1). Therefore, one should use the terminology *horizontal axis* or *vertical axis* clothes washers and not front loading or top loading clothes washers to refer to the two distinct technologies.

Usage of Horizontal Axis and Vertical Axis Machines

As we have seen, the main difference between the two systems is in the mechanical action during the washing. The agitator of a vertical-axis machine confines the movement of the clothes more than the gravitational movement created by the motion in a horizontal drum. Vertical axis manufacturers are trying to develop an agitator design that limits the possible wear and tear of the clothes. Bad design can reduce the lifetime of the clothes. An unbalanced load is still a significant problem for vertical axis machines, despite efforts from manufacturers to design better suspension systems for the tub. This balancing problem is non-existent for the horizontal-axis machine [1]. Another problem that is encountered when using a vertical-axis washer is its poor washing performance when it is used at its maximum capacity. The clothes sitting on top of the load cannot be entirely soaked to receive the necessary mechanical action. They can only be

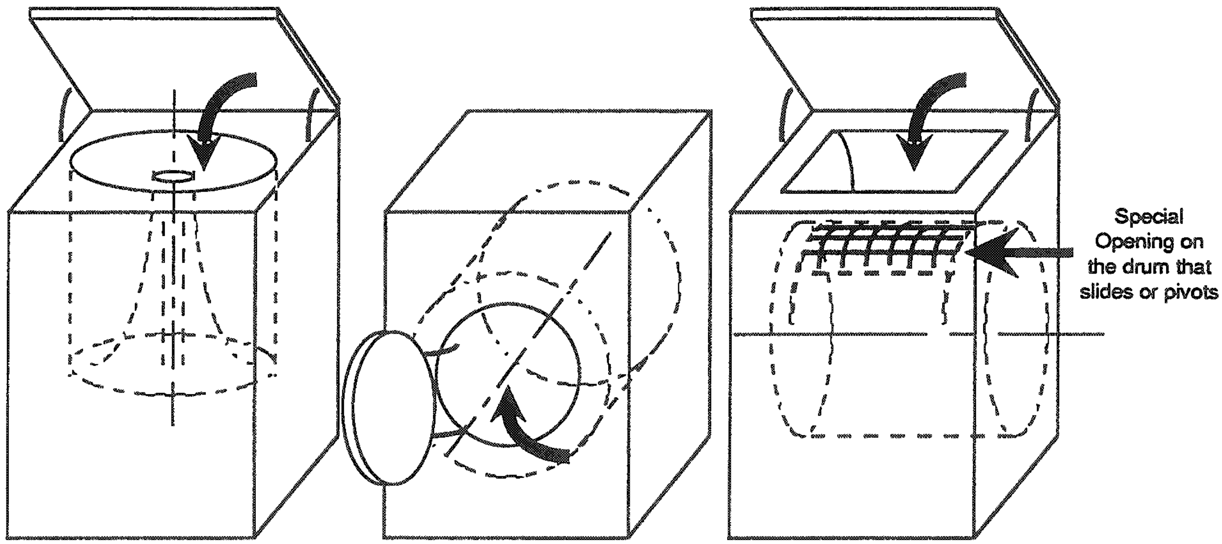

Figure 1. The Different Types of Automatic Clothes Washers

partially washed. Table 1 summarizes the advantages and inconveniences of the two technologies.

PERFORMANCE ANALYSIS

Parameters for Clothes Washers

The most important parameter is obviously the capability of the machine to wash the clothes. There are certainly several ways to measure washing performance. A comparison test performed by the Consumers Union [1] found that all manufacturers of both vertical axis and horizontal axis machines fully meet these cleanability results. However, our interest is in the way the washing is achieved. To run a washing machine one needs water, energy and detergent. Energy is used to run the motor (for mechanical action), the pump (for water circulation and draining), and to heat water at the right washing temperature. The amount of detergent is proportional to the amount of water used during the wash cycle. Because of their specific designs, the two washer technologies use energy, water and detergent in different ways.

As shown in Figure 2, a vertical-axis machine requires that the water covers the entire load. For a horizontal-axis machine, water needs to fill, at most, one third of the tub capacity. The rotation of the drum around its axis forces the clothes to fall by gravity into the water-detergent solution. This is the main reason why horizontal axis machines consume less water, and therefore less energy and detergent, than vertical axis machines.

U.S. DOE Test Procedure for Clothes Washers

The U.S. DOE Test Procedure [2] defines the measurement of annual energy consumption as well as an energy factor for clothes washers. Energy calculations are based on the Temperature Usage Factors (TUF) which correspond to percentages allocated to the usage of temperature selections. A maximum of five wash/rinse temperature selections are possible. These are Hot Wash/Warm Rinse (Hot/Warm), Hot/Cold, Warm/Warm, Warm/Cold, Cold/Cold. Hot corresponds to 140°F, Warm to 100°F and Cold to 60°F. We will consider only three setting machines, corresponding to cold

Table 1. Advantages and Inconveniences of the Two Types of Clothes Washers

	Vertical Axis	Horizontal Axis
Load/Unload	Top Loading	Top Loading but multiple openings can be an inconvenience (lid + door of the drum)
Wear and Tear	Lifetime of clothes can be shortened	Minimal
Load Balancing	Problematic	None
Drying	Needs another appliance	Design allows some models to also dry clothes

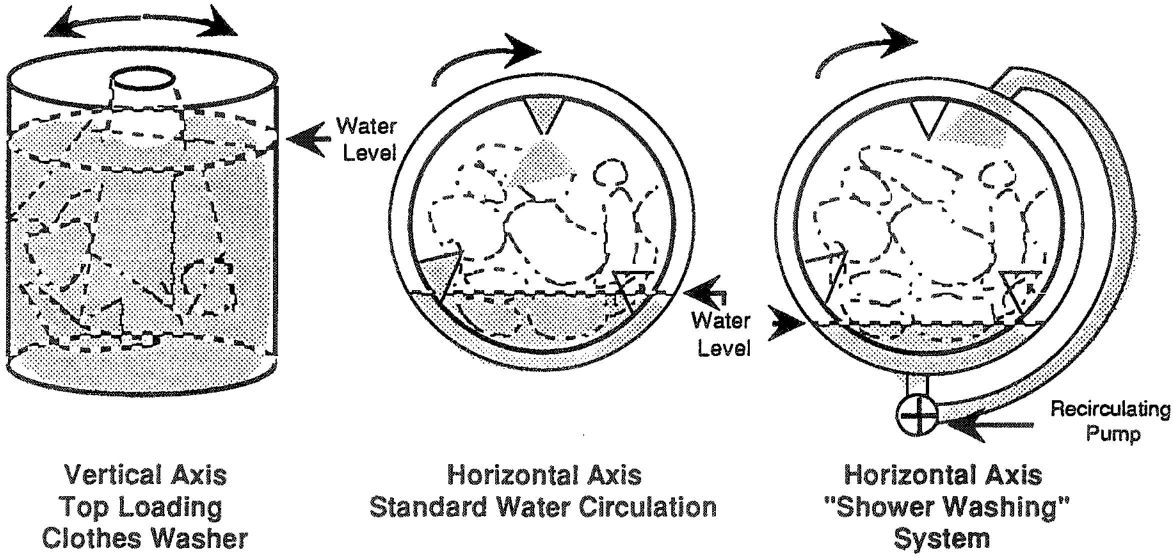

Figure 2. Water Level in a Clothes Washer

rinse-only washers (settings are Hot/Cold, Warm/Cold and Cold/Cold). For each temperature selection, the washer is tested twice, once at maximum fill and once at minimum fill. For each run, electricity and total hot water consumptions are recorded. The total energy consumption is calculated as:

$$E_{annual} = \Omega * E_{total} \text{ (with } \Omega = 416 \text{ cycles/year)} \quad (1)$$

$$E_{total} = E_{machine} + E_{hotwater} \quad (2)$$

$E_{machine}$ is the machine electrical energy consumption in kWh/cycle

$E_{hotwater}$ is the hot water energy consumption in kWh/cycle

If the water is heated with an electric water heater:

$$E_{hotwater} = \mu * \Delta T * \{\Sigma_i TUF_i * (0.72 * V_i max + 0.28 * V_i min)\} \quad (3)$$

If the water is heated with a gas water heater:

$$E_{hotwater} = \mu * \Delta T * \{\Sigma_i TUF_i * (0.72 * V_i max + 0.28 * V_i min)\} * 3412/e \quad (4)$$

i = number of wash/rinse settings

μ = 0.0024 kWh/Gal/°F

TUF_i = Temperature Usage Factors at setting i;

ΔT = 90°F

$V_i$max, $V_i$min: maximum and minimum fill volumes at setting i (Gal)

e = 0.75 : assumed gas water heater recovery efficiency

3142 : conversion factor, Btu/kWh (if $E_{hotwater}$ in Btu/cycle).

The energy factor of the clothes washer is defined as:

$$EF = C / E_{total} \quad (5)$$

EF is expressed in ft^3/kWh

C is the capacity of the tub in ft^3.

Ambiguities of the US DOE Test Procedure

Several ambiguities exist in the present version of the US DOE test procedure. Some affect the energy consumption calculations, others concern discrepancies between horizontal axis machines and vertical axis units. First of all, the temperature usage factors in the DOE test procedure have been based on a survey made by Procter & Gamble in 1975. Procter & Gamble data have been periodically updated through subsequent surveys. As seen in Table 2, the last data collected in 1988 show a significant difference in annual washer use as well as temperature selections compared to the DOE test procedure assumptions.

As we can see in equations 3 and 4, the DOE test procedure assumes 100% efficiency for an electric water heater and 75% efficiency for a gas water heater. These efficiencies do not correspond to actual field data. Annual water heater efficiencies found in typical households are 85% for an electric water heater and 52% for a gas water heater. New water heaters are required to have a minimum energy factor of 88% for electric storage heater (capacity of 52 Gallons) and 54% for gas-fired storage type heater (capacity of 40 Gallons). The DOE test procedure is based on recovery efficiency and ignores the water heater jacket losses.

In the definition of the energy factor, the clothes washer capacity (C) in ft^3, is for a vertical axis unit, the volume of the tub when filled to the top of its rim. For a horizontal axis machine, the capacity C is the drum volume. Thus for a horizontal axis unit, the capacity C corresponds to the total volume available for the washing load. However, for a vertical axis unit, C is higher than the total volume available for the washing load since this washing load volume (clothes + water) will never exceed the tub capacity at maximum fill for obvious reasons of overflowing as well as poor washing performance. Since the energy factor is directly proportional to C, it will be higher for a vertical axis washer than for a horizontal axis washer having the same washing capability (in terms of Lbs of clothes washed per cycle) and the same energy consumption. Therefore, the present energy factor definition is more favorable to the vertical axis unit.

Also, the DOE test procedure specifies that vertical axis clothes washers shall be tested *without* a test load as opposed to a horizontal axis unit which shall be tested *with* a test load. This is an unequal condition to impose on the horizontal axis machine because the additional load of the clothes would cause more mechanical and electrical energy ($E_{machine}$) to be consumed by the unit during the test.

Table 2. Usage and Temperature Usage Factors From Procter & Gamble, 1975 and 1988

Wash/Rinse Selection (i=3)	TUF 1975 (DOE Test Procedure)	TUF 1988 (Procter & Gamble)
Cycles/year	416	380
Hot/Cold	0.30	0.19
Warm/Cold	0.55	0.51
Cold/Cold	0.15	0.30

Using Federal Trade Commission Data

The Federal Trade Commission (FTC) requires that all clothes washers sold in the United States display a label showing the annual cost to run the appliance. Two figures in US Dollars are reported, one if the machine will use hot water from an electric water heater and one if it will use a gas water heater. The Federal Trade Commission is in charge of collecting the test data and printing the labels containing this information. The energy calculations are based on the DOE test procedure. A simple calculation allows one to use the two dollar figures on the label to compute the average hot water and electric machine consumption of the clothes washer under study. Let's call \$E and \$G the FTC costs on the label which represent the total cost to run the washer with an electric water heater and a gas water heater, respectively. If \$e and \$g are the unit costs of electricity (\$/kWh), and gas (\$/MBtu), one can rewrite in different terms, equations (1) & (2) as:

$$\$E = \Omega * [\$e * E_{machine} + \$e * E_{hotwater}elec] \quad (6)$$

$$\$G = \Omega * [\$e * E_{machine} + \$g * E_{hotwater}gas] \quad (7)$$

Equations (3) & (4) can be written as:

$$E_{hotwater}elec = 0.0024 * 90 * V \qquad = A * V \quad (3)$$

$$E_{hotwater}gas = 0.0024 * 90 * V * 3412/e = B * V \quad (4)$$

Where $V = \Sigma_i TUF_i * (0.72 * V_i max + 0.28 * V_i min)$ (in Gallons)

V can be considered as the average hot water consumption per cycle (in Gallons/cycle). So one can rewrite (6) and (7) as:

$$\$E = \Omega * [\$e * E_{machine} + \$e * A * V] \quad (8)$$

$$\$G = \Omega * [\$e * E_{machine} + \$g * B * V] \quad (9)$$

Solving for V and Emachine, we can rewrite (8) & (9) as:

$$V = (\$E - \$G)/[\Omega * (\$e * A - \$g * B)] \quad (10)$$

$$E_{machine} = \frac{\$E * \$g * B - \$G * \$e * A}{\Omega * \$e * (\$g * B - \$e * A)} \quad (11)$$

As we can see, the two FTC data (\$E and \$G) allow us to easily get V, the average hot water consumption, and $E_{machine}$, the total electrical machine consumption.

NOTE: One can use this procedure to study dishwasher consumption as well since FTC labels are also a requirement for them.

Baseline Data

To illustrate how horizontal axis washers consume less energy and water than vertical axis machines, we will consider a base case for each of the two clothes washer technologies. Using FTC data and the equations above to get the water and energy consumption, a typical vertical axis unit is defined. For the horizontal axis base case, we will simply use the only American made clothes washer of that type. Equations (10) and (11) were used to go from the FTC label data to the following engineering data summarized in Table 3. Energy and water use data correspond for the second and third columns to the DOE test procedure and for the fourth and fifth columns to the Procter & Gamble data.

SAVINGS ESTIMATION AND ECONOMICS

Energy, Water and Detergent Savings

Using the 1988 Procter & Gamble data presented in Table 2, we have updated DOE test procedure data in Table 3 (columns 2 and 3) and present the energy and water usage for present field usage (columns 4 & 5). As stated earlier, despite the difference in tub capacity, the two units described in Table 3 can handle the same amount of washing load. We can see how the DOE energy factor is not the best characteristic to describe the real energy efficiency of a clothes washer. We propose that an energy factor defined as the ratio of washing load weight over the energy consumption would better describe the energy efficiency of a washing machine. According to the test procedure, the test load weight is 3 Lbs for the minimum fill run and 7 Lbs for the maximum. Using the same weighting factor as in Equation (3), we get an average weight for the test load of 5.88 Lbs. The last row of Table 3 presents the proposed energy factor.

Table 3. Base Case Energy and Water Data

	DOE Test	DOE test	P & G 1988	P & G 1988
Clothes Washer Type	Vertical Axis	Horizontal Axis *	Vertical Axis	Horizontal Axis *
Capacity (ft^3)	2.40	2.25	2.40	2.25
Hot Water (Gal/cycle)	8.3	2.6	6.4	2.0
Total Water (Gal/cycle)	33.0	20.0	33.0	20.0
Machine (kWh/cycle)	0.24	0.13	0.24	0.13
DOE Energy Factor ** (ft^3/kWh/cycle)	1.18	3.22	1.29	3.52
Total Energy Use** (kWh/year)	846	291	709	243
Proposed Energy Factor** (Lbs of Clothes/kWh/cycle)	2.89	7.68	3.15	9.19

*White Westinghouse, Model LT800L
** a field efficiency of 85% is assumed for an electric water heater when using the 1988 Procter & Gamble data.

Economics and Payback Calculations

For the estimation of the total costs to run a clothes washer, we consider the cost of energy (electricity and gas), the cost of water and the cost of detergent. For each one of the washer technologies we have two scenarios: the first one uses an electric water heater (having an efficiency of 85%), the second one is with a gas water heater (with an efficiency of 52%). Costs are based on national averages of fuel, water and detergent costs projected in 1993 and are summarized in Table 4.

Retail costs of vertical axis clothes washers are estimated according to a Consumers Union's study [5]. The incremental retail cost for a horizontal axis machine compared to a vertical axis machine is estimated at $200. We consider this value to be a maximum. This incremental retail cost will drop if horizontal axis machines were to become more popular. As we can see in Table 5, the payback periods to switch from a vertical axis machine to a horizontal axis unit are 2.16 and 2.76 years when water is heated by an electric water heater and a gas water heater, respectively.

FURTHER IMPROVEMENTS

Design Options for Horizontal Axis Clothes Washer

Several major improvements can be achieved for the horizontal axis machine that we consider as our base case. Following is a list of potential design options aimed at reducing energy and water use.

Internal Flow-Thru Water Heater. In Europe, all clothes washers have an internal water heater. A flow-thru design water heater has the advantage of heating efficiently as well as taking very little space. By using a flow-thru heater, one limits the standby losses on the water heater. The water is heated with 96% efficiency [6] and not with 52% or 85% as calculated previously. Incremental cost is estimated to be $5 [6].

Water Spray. As seen in Figure 2, water can be recirculated and sprayed on top of the load instead of the usual recirculation method where water is dropped on the load while the drum rotates. Water recirculates 85% more with a spray system. An estimate of 20% of total water may be saved, but a

Table 4. Fuel, Water and Detergent Cost

Items	$1993
Electricity (4)	7.90 ¢/kWh
Gas (4)	5.73 $/Therm
Water (4)	1.957 $/10^3 Gallons
Detergent (3)	0.1810 $/dose*

* dose = 3 oz., for a regular load on an vertical axis machine.

Table 5. Costs of Running a Clothes Washer

Annual Costs (in $1993)	Vertical Axis	Horizontal Axis
Machine Electric	$7.2	$3.9
Electric Hot Water	$48.8	$15.3
Gas Hot Water	$19.8	$6.2
Water	$24.5	$14.9
Detergent *(1)	$68.8	$22.9
Total Using Electric Hot Water	$149.4	$57.0
Total Using Gas Hot Water	$120.3	$47.9
Retail Cost ($1990)	$475	$675
Life Cycle Cost Electric Hot Water *(2)	$1890	$1215
Life Cycle Cost Gas Hot Water *(2)	$1615	$1129
Payback Using Electric Hot Water *(3)	-	2.16 Yr
Payback Using Gas Hot Water *(3)	-	2.76 Yr

*(1) assume 1 dose/wash for vertical axis; 1/3 dose/wash for horizontal axis wash
*(2) assume 15 years for life time 7% discount rate.
*(3) payback from switching from a vertical axis clothes washer to a horizontal clothes washer.

recirculating pump must be installed. Incremental cost can be high because of redesign.

Plastic Drum. By replacing the stainless steel drum, a plastic drum would absorb less heat and would be lighter to rotate, thus some energy savings could be expected. Additional cost should be negligible. Users may be reluctant to purchase washers with the new tub design because of its plastic appearance. No data is available to evaluate potential savings.

High Spin Speed. Water extraction by mechanical energy in a clothes washer is more efficient than by thermal energy in a clothes dryer. A regular spin speed in a tumble clothes washer is around 500 to 600 rpm. In Europe, some new clothes washers have spin speeds reaching 1,400 rpm and extract more water than previous models. Wrinkles are limited because of a very precise spin profile where the high spin speed is alternated with a very slow spin in the opposite direction. No savings can be computed with the present DOE test procedure.

Control of Load Weight and Water Level. Some European manufacturers [7][8] already propose some smart tumble washers that weigh the load and recognize the texture of linen. A microprocessor accurately controls the amount of water, the best turning pace and wash time, the best rinsing-water volume and length, and the best spin-drying time. The machine weighs the load before the wash cycle starts by measuring the amount of electrical demand of the motor to rotate the drum one revolution. The dry load weight is proportional to the torque of the tub, and the torque is proportional to the electrical demand. The machine then fills the tub with water until the clothes can not absorb anymore water. With data on the weight of the dry load and the amount of water it can absorb, the machine recognizes the texture of linen.

Advanced Controls and Optical Controls of Wash and Rinse Water. The next logical step in developing even smarter clothes washers would be to incorporate advanced controls. By combining a microprocessor and some optical devices, the controls are able to keep track of the cleaning process as well as the rinsing action so as to determine when the washing cycle is completed. Energy, water and detergent would then be used at the minimum requirements. Two teams have been working separately on the new washing controls [9][10], proving the technical feasibility of advanced electronics in washing machines. Recently a Japanese manufacturer, Matsushita Electric Industrial Co. has introduced a machine that not only use sensors but also fuzzy logic controllers to judge the size and dirtiness of the load and to decide the optimum cycle type times and water level [11].

However no results are available to evaluate the potential savings of that design option. Also, since the DOE test procedure does not involve washing performance analysis, the impact of such advanced controls can not be estimated. Field testing would be the most appropriate way to compute water, energy and detergent savings.

Rinse Water Saver Tank. A German manufacturer has developed a prototype of a rinse water saver tank [12]. The tank is placed beside the clothes washer so as to save the rinse water for reuse during the wash cycle for the next wash load. To be reused, water is treated by Ultra-Violet light, emitted by two fluorescent lamps. Significant amounts of water are saved. Two fluorescent light bulbs must however be on continually.

CONCLUSION

Substantial energy savings can be obtained by switching from a vertical axis to a horizontal axis clothes washer technology. These energy savings correspond to 61% of the actual consumption of a standard size vertical axis clothes washer. Water and detergent savings are also significant, 39% and 66% respectively. Impacts on a better environment are obvious. We have also seen how further improvements in energy efficiency for the horizontal axis machine are possible. The issue is how to find ways to increase market share for horizontal axis machines.

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