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Selecting Cleaning Processes for Electronics Defluxing: Total Cost of Ownership

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Abstract
Electronics manufacturing process engineers are faced with significant challenges when selecting a cleaning system as a consequence of the wide ranges of cleaning processes and equipment. Currently available cleaning systems include aqueous processes, semi-aqueous processes, monosolvent vapor degreasing and co-solvent vapor degreasing; while equipment options include inline, batch, centrifugal and ultrasonic immersion. When matching the right process with the right equipment for a specific application, many other factors must be considered including performance, capital expense, SHE (safety, health and environmental) restrictions, throughput, available floor space, chemical compatibility and operating costs and maintenance costs. An analysis of the total cost of ownership of a cleaning process is an important step in choosing the right process. This analysis helps identify the lifetime costs of acquiring, maintaining and operating a process. This paper discusses the factors, advantages and disadvantages that should be considered for each of the commonly used processes in the electronics cleaning industry to help determine the total cost of ownership.

Introduction
The complexity of today's electronics assemblies coupled with high reliability standards in the newer generation of consumer and industrial electronic products has placed increasing importance on product cleanliness. Unfortunately, the selection of flux and/or solder pastes is often made without consideration of the removal method of the residues generated during the reflow process. This can lead to difficult cleaning challenges.

When selecting a cleaning process, the manufacturer must consider a number of factors contributing to the final cost of the board, including throughput, capital expenditures, cleaning agent costs, disposal costs, power requirements, downtime, and preventive maintenance. Each of these items contributes to the total cost of ownership for the cleaning process. The American Society for Testing and Materials (ASTM) Method D6361 (Standard Guide for Selecting Cleaning Agents and Processes) provides guidance for engineers in selecting the best-fit cleaning agent and process for industrial cleaning taking into account environmental pollution prevention factors. Though this guide was written for processes for manufacturing, overhaul and maintenance in industrial operations, it provides valuable guidance which can be utilized in other industries and should be considered an additional tool.

Total Cost of Ownership
A good total cost of ownership analysis systematically addresses all costs associated with a cleaning process and helps bring to the surface hidden or non-obvious costs. Often, only the initial equipment cost and chemical cost per gallon are considered when selecting processes. Though the initial capital cost may be an important factor, it often may be only a small part of the total cost of ownership. The non-obvious costs, often unrelated to the initial equipment purchase price, could strongly influence the best choice in selecting a process. To make an informed comparison, all costs should be analyzed based on a total cost of ownership approach. The cost of ownership should reflect operating and opportunity costs, in addition to the capital costs. Operating costs include direct costs such as chemicals, power and disposal; while opportunity costs include indirect costs, lost opportunity or production time caused by repairs, preventive maintenance downtime, bath monitoring and chemical change-outs.

Whether one is an OEM or a contract manufacturer, the ultimate objective is to reduce the manufacturing cost per board. In this paper, the cleaning cost per board for the common processes described herein is estimated based on a set of assumptions to give the users a guide for comparing all costs involved in each of the cleaning processes. Some assumptions are applied to all cleaning processes such as water, electricity and space costs; and some assumptions are unique to the process, such as cleaner or waste disposal costs. All assumptions are described in the next section. The capital and operating costs for each process have been calculated and are presented in the following tables to illustrate the total cost of ownership. Since opportunity costs are unique to each situation, they have not been included in the present analysis, but are discussed later.

Description of Cleaning Processes

The common cleaning processes for electronics applications can broadly be classified into five primary categories.

1) Aqueous Inline
2) Semi-Aqueous Inline
3) Aqueous Batch Spray-in-Air
4) Co-Solvent Vapor Degreasing
5) Monosolvent Vapor Degreasing

Other less widely used electronics cleaning processes such as those involving centrifugal and ultrasonic immersion systems are not discussed in this paper.

Aqueous Inline Systems

Aqueous inline cleaning systems typically consist of three steps: wash, rinse and dry. Each of these individual steps may include one or more stages. Boards travel through the machine on a stainless-steel conveyor belt at a predetermined rate of speed. There are high-pressure spray bars above and below the belt in both the wash and rinse sections. A typical inline machine uses a pre-wash, wash, chemical isolation (chem-iso) section, two rinses and a dry section. The pre-wash and wash sections typically use a chemical concentration of 10-25% cleaning chemistry operating at 140-165°F. The cleaner is usually a saponifier mixed with other ingredients to improve performance, inhibit corrosion, and reduce foaming. The chem-iso section is used to prevent contamination of the rinse sections by reducing the amount of drag out of the wash solution into the rinse sections as the boards travel through the machine. The rinse section of the machine uses deionized water usually heated to 140-165°F. The rinse water is either sent to drain or to a water treatment system for recycle. The drying section is typically either heated or unheated forced air. Inline systems have the highest throughput capacity.

Semi-Aqueous Inline Systems

The semi-aqueous inline system is similar to the aqueous system in machine design. In the semi-aqueous cleaning process, a water-rinseable cleaning solvent is used in the wash step to remove flux and other solvent soluble residues. The cleaning solvent may be in either undiluted or in emulsion form. The wash step can be a spray-in-air or spray-under-immersion arrangement with sprays both above and below the conveyor belt. After the wash step, the wash material is rinsed multiple times with fresh deionized water, usually in a spray-in-air arrangement. Many inline semi-aqueous cleaning systems follow the wash step with a recirculating emulsion rinse step. This step is a bath made up of a mixture of the cleaning solution and water which is isolated from the rinse stages. Many semi-aqueous cleaning solutions can be separated from water which allows for a cleaning process that does not require a rinse waste stream. The parts are dried with heated or unheated forced air in the drying section. As stated above in the aqueous inline description, inline systems have the highest throughput capacity.

Aqueous Batch Spray-in-Air

Batch aqueous spray-in-air systems are typically referred to as batch dishwashers due to their resemblance to household dishwashers. These systems can be single-chamber or multi-chamber units, though the former are more widely used. The units operate through the use of rotating spray bars which spray the cleaning solution over the boards which are held in racks. The complete cleaning cycle is typically an optional prewash followed by a wash and multiple rinse cycles. The temperatures used for cleaning and rinsing the circuit boards range from 140°F to 180°F. The cleaning agent can either be reused or disposed after a single cycle. Because the process must go through a complete cycle of wash, rinse and dry before the next cycle can begin, the throughput rate is low.

Co-Solvent Batch Vapor Degreasing Systems

The patented co-solvent vapor degreasing process is similar to a conventional vapor degreasing process and requires a two-sump vapor degreaser. The process uses a high-boiling solvent blend or Solvating Agent (SA) that is mixed with a relatively low-boiling, high-vapor-pressure, non-flammable solvent or Rinse Agent (RA). The boil sump consists of both the SA and the RA, while the rinse sump consists exclusively of RA. The operating temperature of the boil sump is controlled by the SA to RA ratio. The RA boils in the boil sump creating a vapor blanket. Cleaning only takes place in the boiling sump where the parts are exposed to the SA, so the parts must be lowered into the boil sump to remove the soil. The parts are immersed in the rinse sump to remove the dissolved soil and SA, and finally raised into the vapor space where the RA condenses on the parts for a final rinse.

Monosolvent Batch Vapor Degreasing Systems

A conventional vapor degreasing system is equipped with either one or more sumps and uses a single solvent, referred to as monosolvent, both as a washing and rinsing agent. A typical vapor degreasing monosolvent is a relatively low-boiling, high-vapor-pressure, non-flammable material that is either a single component or an azeotrope. As the monosolvent boils, it forms a blanket of vapor which is contained within the equipment by cooling coils near the top of the equipment opening. In a one sump degreaser, the part to be cleaned is typically immersed in the vapor phase; the cleaner condenses on the part, cleaning it and carrying the soil away. In vapor degreasers with two or more sumps, the part to be cleaned may be first submerged in the boiling sump to loosen very tough soils, though this is not common. The part may then be (or initially) submerged into the rinse sump or sumps, which are constantly being replenished with clean monosolvent condensed on the cooling coils. The rinse sump or sumps continually overflow into the wash sump, where the contaminants are concentrated. The part is raised into the vapor space where the vapor condenses on the part which acts as the final rinse.

Total Cost of Ownership – Assumptions:
In determining the total cost of ownership, assumptions are based on the best information available to the authors. But these costs will vary across regions and suppliers.

All assumptions used in calculating the total cost of ownership for each process are shown in Table 1. For the purpose of this analysis, it is assumed that all the cleaning processes discussed pass the cleaning requirements. Previous presentations have described results of cleaning effectiveness of the processes discussed on various flux residues (Soma et al.). Capital, operating and total cleaning cost per board for each of the processes is shown in Table 2. The capital costs are amortized over ten years using an interest rate of 10%.

The generic assumptions listed below are applied to all processes.
Electricity cost: $0.12/kWh
DI water cost: $0.08/gal
Space cost: $125/sq ft
Labor costs are not included, as they are assumed to be the same for all processes.

Chemical costs:
Aqueous alkaline cleaner: $38/gal
Semi-aqueous cleaner: $58/gal
Solvent (Monosolvent vapor degreasing): $31/gal
Solvating Agent (Co-Solvent vapor degreasing): $65/gal
Fluorinated Rinse Agent (Co-Solvent vapor degreasing): $210/gal

Chemical disposal costs:
Spent non-halogenated solvents having high BTU value (Semi-aqueous cleaner): $50/55 gal container
Spent aqueous cleaning solutions containing organics and lead, tin, copper and/or silver in trace amounts: $170/55 gal container
Spent halogenated solvents: $250/55 gal container
Rinse water disposal: $0.0012/gal

Throughput assumptions:
Board size: 10in. x 10in.
Number of working hours per year: 40 hr/week x 52 weeks = 2080 hr/yr

AQUEOUS INLINE CLEANING PROCESS
This process evaluation uses a standard inline cleaning machine with a pre-wash, wash, chemical-isolation, two rinses and a dryer. The throughput is calculated assuming a double-track feed to the conveyor.

Equipment cost: $170,000
Accessories cost (DI water system): $30,000
Space required: 6 ft x 20 ft
Number of kWh used per hour: 96
Conveyer length: 15 ft
Belt speed: 2 ft/min
Number of boards cleaned per hour (double track): 288
Wash tank capacity: 80 gal
Chemical cost: $38/gal
Concentration of the cleaning agent: 15%
Fluid losses (drag out and evaporative): 5.5 gal/hr
Number of wash solution change-outs per year: 2
DI water usage: 300 gal/hr

SEMI-AQUEOUS INLINE CLEANING PROCESS

This evaluation uses a standard inline cleaning machine with a wash, emulsion chamber with water separator, two rinses and a dryer. The throughput is calculated assuming a double-track feed to the conveyor.

Equipment cost: $200,000
Accessories cost (DI water system): $30,000
Space required: 6 ft x 20 ft
Number of kWh used per hour: 96
Number of boards cleaned per hour (double track): 288
Wash tank capacity: 80 gal
Chemical cost: $58/gal
Concentration of the cleaning agent: 100%
Fluid losses (drag out and evaporative): 0.5 gal/hr
Number of wash solution change-outs per year: 1
DI water usage: 200 gal/hr

AQUEOUS BATCH SPRAY-IN-AIR CLEANING PROCESS

This evaluation uses a standard batch aqueous cleaning unit with a 10-gallon wash tank.

Equipment cost: $40,000
Accessories cost (DI water system): $15,000
Space required: 6 ft x 4 ft
Number of kWh used per hour: 12
Cleaning cycles per hour: 2
Number of boards cleaned per hour: 52
Wash tank capacity: 10 gal
Chemical cost: $38/gal
Concentration of the cleaning agent: 20%
Fluid losses (drag out and evaporative): 0.5 gal/hr
Number of wash solution change-outs per year: 4
DI water usage: 15 gal/load

CO-SOLVENT BATCH VAPOR DEGREASING PROCESS

A two-sump vapor degreaser with sump dimensions of 12in. x 12in. x 18in. and a 120% freeboard is used for this cost analysis. A boil down (a reclamation process wherein the contaminated solvent is distilled in the vapor degreaser to recover the rinse agent and dispose of the contaminated solvating agent) every quarter is assumed.

Equipment cost: $50,000
Accessories cost (hoist): $20,000
Space required: 4 ft x 6 ft
Number of kWh used per hour: 8
Number of boards cleaned per hour: 48
Vapor degreaser sump capacity (boil & rinse): 26 gal
Solvating Agent to Rinse Agent Ratio: 35:65
Solvating Agent cost: $65/gal
Rinse Agent cost: $210/gal
Fluid losses (drag out and evaporative): 1.5 gal/week
Number of boil downs per year (disposing all the Solvating Agent): 4
DI water usage: 0 gal/hr

MONOSOLVENT BATCH VAPOR DEGREASING PROCESS

A two-sump vapor degreaser with sump dimensions of 12in. x 12in. x 18in and a 120% freeboard is used for this cost analysis. A non-fluorinated solvent with a change-out every six months is assumed.

Equipment cost: $50,000
Accessories cost (hoist): $20,000
Space required: 4 ft x 6 ft
Number of kWh used per hour: 8
Number of boards cleaned per hour: 48

Vapor degreaser sump capacity (boil & rinse): 26 gal
Chemical cost: $31/gal
Concentration of the cleaning agent: 100%
Fluid losses (drag out and evaporative): 1.5 gal/week
Number of change-outs per year: 2
DI water usage: 0 gal/hr

Table 1: Assumptions Used in Calculating the Total Cost of Ownership

	Aqueous Inline	Semi-Aqueous Inline	Aqueous Batch Spray-in-Air	Co-Solvent Batch Vapor Degreasing	Monosolvent Batch Vapor Degreasing
No. of Boards Processed/hour	288	288	52	48	48
Equipment Footprint	6’ x 20’	6’ x 20’	4’ x 6’	4’ x 6’	4’ x 6’
Equipment Cost ($)	170,000	200,000	40,000	50,000	50,000
Accessories Cost ($)	30,000	30,000	15,000	20,000	20,000
Cleaning Fluid Cost ($/gal)	38	58	38	65 (Solvating Agent) 210 (Rinse Agent)	31
Power Requirement (kWh/hour)	96	96	12	8	8
Tank Capacity (gal)	80	80	10	26	26
Cleaning Fluid Concentration (%)	15	100	20	35% Solvating Agent 65% Rinse Agent	100
Evaporative and Drag out Losses	5.5 gal/hr	0.5 gal/hr	0.5 gal/hr	1.5 gal/week	1.5 gal/week
Yearly Change-outs	2	1	2	Boil down every quarter	2
Used Fluid Disposal (gal/yr)	160	80	20	36	52
Used Fluid Disposal Cost ($/55 gal)	170	50	170	50	250
DI Water Requirement (gal/hr)	300	200	30	0	0
Rinse Water Disposal (gal/hr)	300	200	30	0	0

Table 2: Cleaning Cost per Board

		Aqueous Inline	Semi-Aqueous Inline	Aqueous Batch Spray-in-Air	Co-Solvent Batch Vapor Degreasing	Monosolvent Batch Vapor Degreasing
Throughput (Boards/hr)		288	288	52	48	48
Throughput (Boards/yr)		599040	599040	108160	99840	99840
Capital Costs	Equipment	$170,000	$200,000	$40,000	$50,000	$50,000
	Accessories	$30,000	$30,000	$15,000	$20,000	$20,000
	Space	$15,000	$15,000	$3,000	$3,000	$3,000
	Initial Fluid Fill	$456	$4,640	$76	$4,141	$806
	Sub-Total	$215,456	$249,640	$58,076	$77,141	$73,806
	Amortized Cost/yr over 10 years	$35,064	$40,628	$9,452	$12,554	$12,012
Operating Cost/yr	Electricity	$23,962	$23,962	$2,995	$1,997	$1,997
	Fluid Make-up (losses)	$65,986	$60,320	$7,971	$12,422	$2,418
	Fluid Make-up (change-outs)	$912	$4,640	$152	$2,366	$1,612
	Used Fluid Disposal	$495	$73	$62	$33	$236
	DI Water	$49,920	$33,280	$4,992	$0	$0
	Rinse Water Disposal	$749	$499	$75	$0	$0
	Sub-Total	$142,023	$122,774	$16,246	$16,817	$6,263
	Total Operating Cost/yr	$142,023	$122,774	$16,246	$16,817	$6,263
Total Cost/yr		$177,087	$163,401	$25,698	$29,372	$18,275
Total Capital Cost/Board		$0.06	$0.07	$0.09	$0.13	$0.12
Total Operating Cost/Board		$0.24	$0.20	$0.15	$0.17	$0.06
Total Cost/Board (Capital + Operating)		$0.30	$0.27	$0.24	$0.30	$0.18

Discussion

The selection of a cleaning process will depend on several factors, first and foremost being the required throughput. Based on the throughput requirement an inline, a multi-batch or a single batch system is selected. The choice of chemistry then will depend on various factors such as cleaning effectiveness, compatibility with substrates, SHE requirements and regulatory restrictions. When multiple chemistries meet the requirements, the total cost of ownership should be used to choose the best alternative.

As can be seen from Table 2, even though the total cost/year for high-volume operations using inline cleaning equipment are substantially higher than low-volume operations using batch equipment, the total capital cost/board can be lower for inline systems. However, the operating costs/board for an inline is generally higher than for batch operations. If high throughput is not required, the monosolvent batch vapor degreasing offers the lowest total cost/board amongst the processes evaluated, followed by aqueous batch cleaning If high throughput is required, both the aqueous and semi-aqueous processes offer similar total cost/board. The total cost/board for the batch co-solvent process is high due to the expensive fluorinated solvents used in the process. However, new fluorinated solvents offering similar performance are now available at lower prices.

While the above evaluation only took capital and operating costs into account, other costs such as opportunity costs can be included to get a more comprehensive analysis. Opportunity costs are the most overlooked costs when selecting a cleaning process, as they are not very obvious. The opportunity costs are unique to each situation and may or may not be of significance depending on the situation. Some examples of opportunity costs include:

- A typical vapor degreaser operating a co-solvent process requires a boil down cleaning cycle every quarter as a part of preventive maintenance to remove the contaminated Solvating Agent. Each boil down requires taking the vapor degreaser off-line for a day. The lost production for four days in a year would mean the loss of production capability of 1536 boards/yr (4 days x 8 hr/day x 48 boards/hr). Assuming a profit of $10/board, that would amount to $15,360 in lost income.
- A typical vapor degreaser operating a monosolvent process requires a solvent change-out every six months to remove the contaminated solvent. Each change-out would typically require taking the degreaser off-line for half-a-day. This would amount to lost production capability of 384 boards/yr (2 x 4 hr/day x 48 boards/hr). Assuming a profit of $10/board would amount to $3,840 in lost income.
- An inline cleaning system which typically has multiple moving parts may require a down time of 4 days/ yr for preventive maintenance or breakdown repairs. The lost production due to this amounts to 9216 boards/yr (4 days x 8 hr/day x 288 boards/hr). Assuming a profit of $10/board would amount to $92,160 in lost income.
- Where space is a premium, a saving of 96 sq ft can be realized by going for batch equipment instead of an inline machine, amounting to $12,000 in direct cost of the space, besides the opportunity costs of using that space for other operations.

An attempt has been made in this paper to provide a tool to systematically analyze the costs involved in selecting and operating a cleaning process. This total cost of ownership analysis will help process engineers and managers in selecting the lowest cost, best-fit process.

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