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I am submitting herewith a thesis written by Rodney Joseph Mackereth entitled "Immersion Tanks and Batch Cabinet Spray Equipment Costs". I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Chemical Engineering.

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Immersion Tanks and Batch Cabinet Spray Equipment Costs

A Thesis

Presented for the

Master of Science

Degree

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Rodney Joseph Mackereth

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ABSTRACT

The manufacturing sector has experienced a transition with its' industrial cleaning methods, turning away from chlorinated solvent vapor degreasing towards more environmentally acceptable alternative industrial cleaning processes. In support of this change, it has become necessary to develop tools that allow preliminary economic evaluations of these alternatives. The research detailed in this thesis was undertaken to further develop the economic tools of the Solvent Alternatives GuidE (SAGE) computer program originally developed by the Environmental Protection Agency to facilitate this transition. The costs of industrial cleaning equipment were investigated for aqueous, semi-aqueous, and hydrocarbon cleaning technologies. The costs of two basic equipment configurations were identified as capable of being modeled, immersion tanks and batch cabinet spray washers. This thesis details three cost models for immersion tanks as a function of their volume. The models differ on the materials of construction, carbon steel, stainless steel, and both carbon and stainless steel construction. In addition, eight process options were identified and modeled for immersion tanks. These options were ultrasonics, mechanical agitation, particle filtration, rotating basket mechanism, immersed jets, air sparging, vapor extraction, and oil skimmers. An additive procedure is suggested from which a total estimate of the cost of immersion equipment can be made. Also detailed, is a cost model for batch cabinet spray equipment. This model, suitable for estimating the cost of both top-load and front-load equipment configurations, is a function of total equipment volume, i.e., spray chamber volume plus reservoir volume. A comparison of cost estimates for three immersion tanks between those generated using the aforementioned cost models and vendor quotes demonstrated that the models were capable of providing cost estimates within the ±30 per cent accuracy levels required of a

study estimate in traditional process engineering design. Finally, the annualized costs of an alternative process are projected in which the calculations performed detail some of the design considerations necessary to evaluate an alternative industrial cleaning process.

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NOMENCLATURE

SYMBOL

ABBREVIATIONS

CFC	Chloroflourocarbons
AC	Aqueous acidic based alternative cleaning agent
AL	Aqueous alkaline based alternative cleaning agent
DBE	Dibasic esters
EPA	United States Environmental Protection Agency
HC	Hydrocarbon based alternative cleaning agent
NMP	N-methyl2-pyrrolidone
SAGE	Solvents Alternatives GuidE
TCE	Trichloroethylene
TCA	Trichloroethane
TE	Terpene based alternative cleaning agent
KHz	Kilohertz
SNAP	Significant New Alternatives Policy
FOB	Free-On-Board
PCB	Printed Circuit Board
POTW	Publicly Owned Treatment Works

1.0 INTRODUCTION

1.1 Problem Statement

Industrial cleaning has been experiencing a transformation for the past decade or so. It involves the movement of the manufacturing industry away from traditional vapor degreasing towards alternative cleaning methods. It began with the designation of chlorinated degreasing solvents such as trichloroethylene, 1,1,1, trichloroethane, chloroflourocarbons (CFC's), and methylene chloride as hazardous chemicals; eventually leading to the production phase-out of CFCs and 1,1,1, trichloroethane all together. As a result of these environmental regulatory measures, industrial manufacturing concerns have found themselves investing time, effort, and capital into investigating the cleaning alternatives that exist.

To make such investigations possible, sources of information are needed as well as evaluation and reference tools. To assist industry in this regard, the Solvents Alternatives GuidE (SAGE) was developed by the Environmental Protection Agency (EPA). As a reference tool, it provides general information about the available alternatives as well as educates its' users on the kind of cleaning process questions which need to be asked when considering alternative processes. Such questions concern part size, throughput, geometry, substrate sensitivities, and level of cleanliness desired. The answers to these questions as well as others may suggest one alternative process over another. Additional sources of general information about alternative cleaning processes are obtained through educational or research programs such as the Alternative Solvents: Cleaning, Testing, and Evaluation Project conducted by the Department of Chemical Engineering at the University of Tennessee. Through this program, information can be

obtained concerning the potential viability of an alternative wash agent and associated cleaning process for a particular application as a result of actual laboratory testing.

Additionally, an entire new industry of wash agent vendors and equipment manufacturers has developed to accommodate the transformation to alternatives in industrial cleaning. This has done much to fill the information void on the available alternatives. Although, the value of the vendor contribution towards the education of manufacturers on industrial cleaning matters cannot be understated; their intent remains to sell a product. This fact coupled with the diversity of alternative wash agents and equipment promoted by various vendors has given rise to a particular feeling of anxiety among industrial concerns as each searches for suitable alternatives. Some anxiety is commonly encountered in most settings where the services of vendors are utilized. However the particular dependence on vendors to educate in the industrial cleaning arena has tended to contribute significantly to this feeling.

The attention being given to cleaning alternatives by the manufacturing industry has led to the realization that parts cleaning will no longer be a "one stop shopping" activity as was often the case with traditional vapor degreasing. Most alternative cleaning methods require not only a new wash agent but also new equipment which may be more complex to operate in terms of the number of operating parameters which need to be controlled. Additionally, subtle and not-so-subtle changes in manufacturing are often incurred as a result of the change to an alternative cleaning process. This primarily has meant longer processing times needed to obtain clean parts.

During this industrial cleaning transition, most attention has focused on the alternative wash agents. Questions regarding cleaning agent effectiveness and cleaning parameter optimization for the alternative agents are all issues that must be addressed for an alternative cleaning system to be successfully installed and operated. For industries

long accustomed to the idea of vapor degreasing, there is often an emerging realization upon exposure to alternative cleaning processes that industrial parts washing will be a much more significant step in the economic feasibility of manufacturing processes than before. Thus, an area of concern that has been often overlooked in this transformation has been the economic characterization of the alternatives. The development of tools to address this issue would contribute greatly towards the education of the manufacturing industry to the costs of alternative cleaning methods. Attempts to categorize and model the cost of alternative cleaning systems have been frustrated by the variety of available cleaning equipment as well as the detailed case-by-case engineering of specific cleaning systems.

The purpose of this thesis was to offer investigation of the economics of the industrial cleaning process alternatives based upon a traditional process engineering approach. This was done in the following manner. Models were developed to estimate the cost of immersion tanks of different materials of construction as a function of their volume. Immersion tanks are suitable for use with all three alternative technologies considered by this thesis: aqueous, semi-aqueous, and hydrocarbon cleaning. The primary options available with immersion tanks were identified and an additive procedure was proposed to enable an estimate of the total cost of an immersion tank to be made. Additionally, a model was proposed to estimate the cost of batch cabinet spray wash equipment, suitable for aqueous and emulsion technologies. The cost estimates derived from these models were then compared to actual equipment quotes obtained from vendors. The goal of this research was to deliver cost estimates with an accuracy of ± 30%; the level of accuracy typical of a study estimate in traditional process design. A study estimate requires only flow sheet knowledge of the process and is useful for selecting appropriate technologies at the conceptual design level. Finally, a theoretical

treatment of the projected annualized operating costs for a semi-aqueous process was made based upon a part and throughput of a project participant in the University of Tennessee's Alternative Solvents: Cleaning, Testing, and Evaluation Project. This served to illustrate some of the design considerations necessary for analysis of alternative industrial cleaning processes.

The information contained in this thesis is to be incorporated into the Solvent Alternatives GuidE computer program (SAGE). This will help make it a more complete tool for its' users when investigating alternative industrial cleaning processes to traditional vapor degreasing with chlorinated solvents.

2.0 BACKGROUND

2.1 Process Design

Flow diagrams and associated material and energy balances can provide the information necessary to develop some preliminary cost estimates. Their usefulness depends upon the level of detail they contain. Table 2.1.1 is a list of design estimate categories developed for traditional chemical engineering and process analysis along with the levels of accuracy and detail which generally can be expected [1]. Order-of-magnitude and study cost estimates are used to screen a potentially large number of process alternatives with only minimal input information. As the level of detail provided in the flow diagram is increased, a more accurate design estimate can be derived. Thus the flow sheet provides the basis from which capital and annualized operating costs can be estimated.

Figures 2.1.1, 2.1.2, and 2.1.3 are typical process flow diagrams for the three alternative cleaning processes considered in this thesis; aqueous, semi-aqueous, and hydrocarbon cleaning. All three figures represent typical three stage processes consisting of a wash, rinse, and dry. The importance of each stage is determined by its' impact on the cleanliness level of the part and proceeding manufacturing operations. Thus the number of rinse stages as well as the presence of a drying stage can vary per application based upon cleanliness requirements. However, there are three main criteria against which all alternatives are measured: potential for generation of waste, cleaning effectiveness, and cost. Flow diagrams can be used to determine two of these criteria while cleaning effectiveness must be determined experimentally.

The input-output flow diagram structure allows for identification of all process streams involved in the cleaning process. This serves to illustrate potential waste

Table 2.1.1 Classification of Design Estimates

Estimate Level	Probable Accuracy	Engineering Detail Level
Order-of-Magnitude Estimate (ratio estimate)	±40%	Previous available cost data for similar equipment
Study Estimate (factored estimate)	±30%	Knowledge of costs of major item of process equipment
Preliminary Estimate (scope estimate) (budget authorization estimate)	±12%	Sufficient data to permit the estimate to be budgeted. All known process support items are included.
Definitive Estimate (project control estimate)	±6%	Complete detailed engineering data
Detailed Estimate (contractor's estimate)	±3%	Complete engineering drawings, specifications, and site surveys.

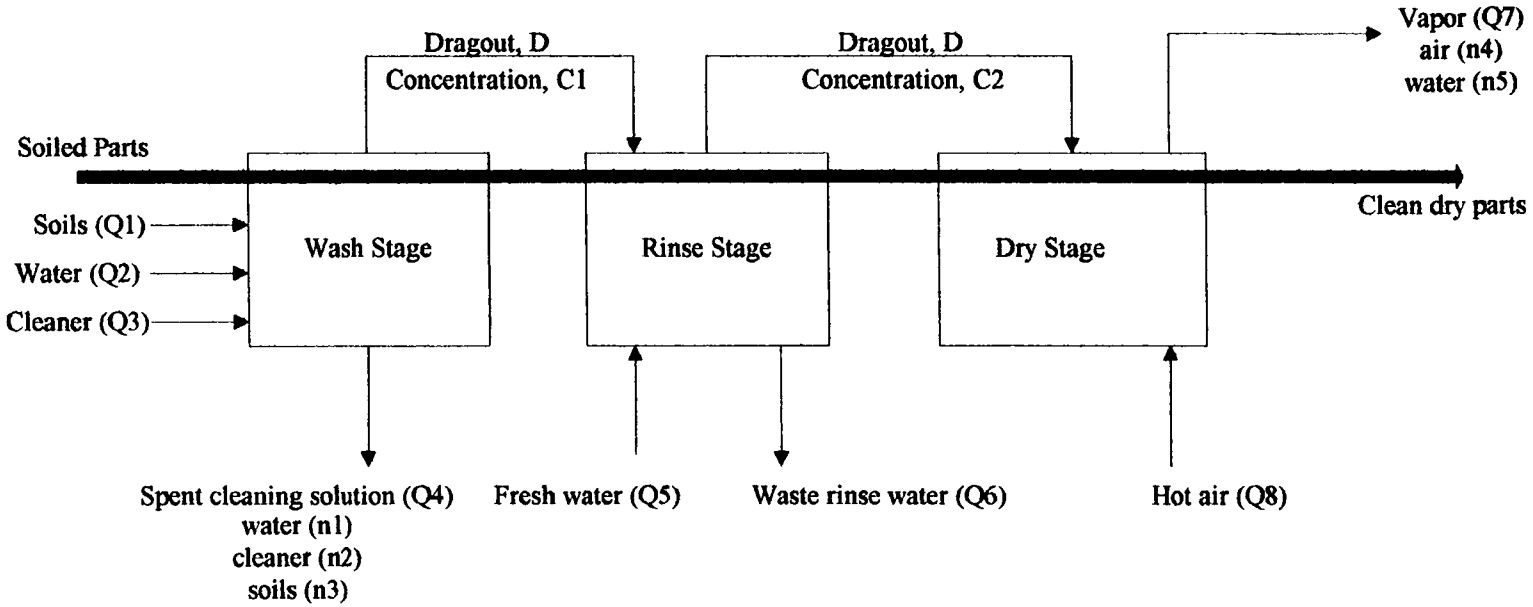

Figure 2.1.1 Aqueous Process Flow Diagram

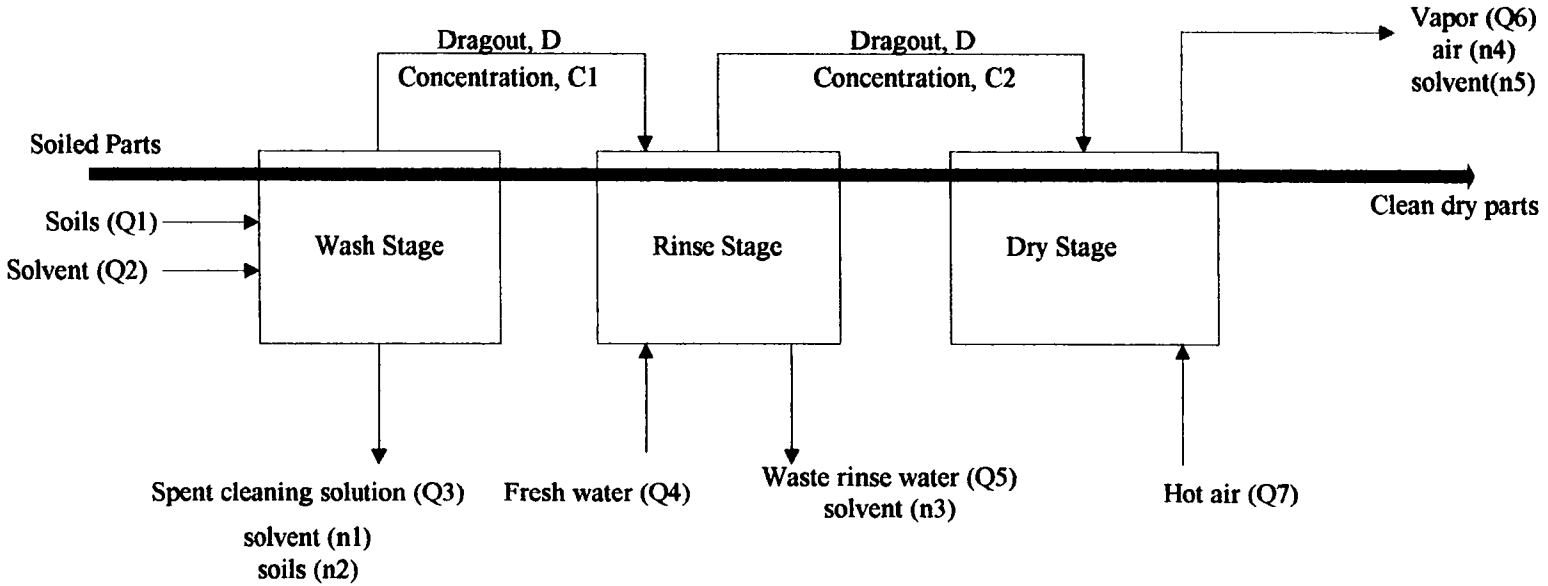

Figure 2.1.2 Semi-Aqueous Process Flow Diagram

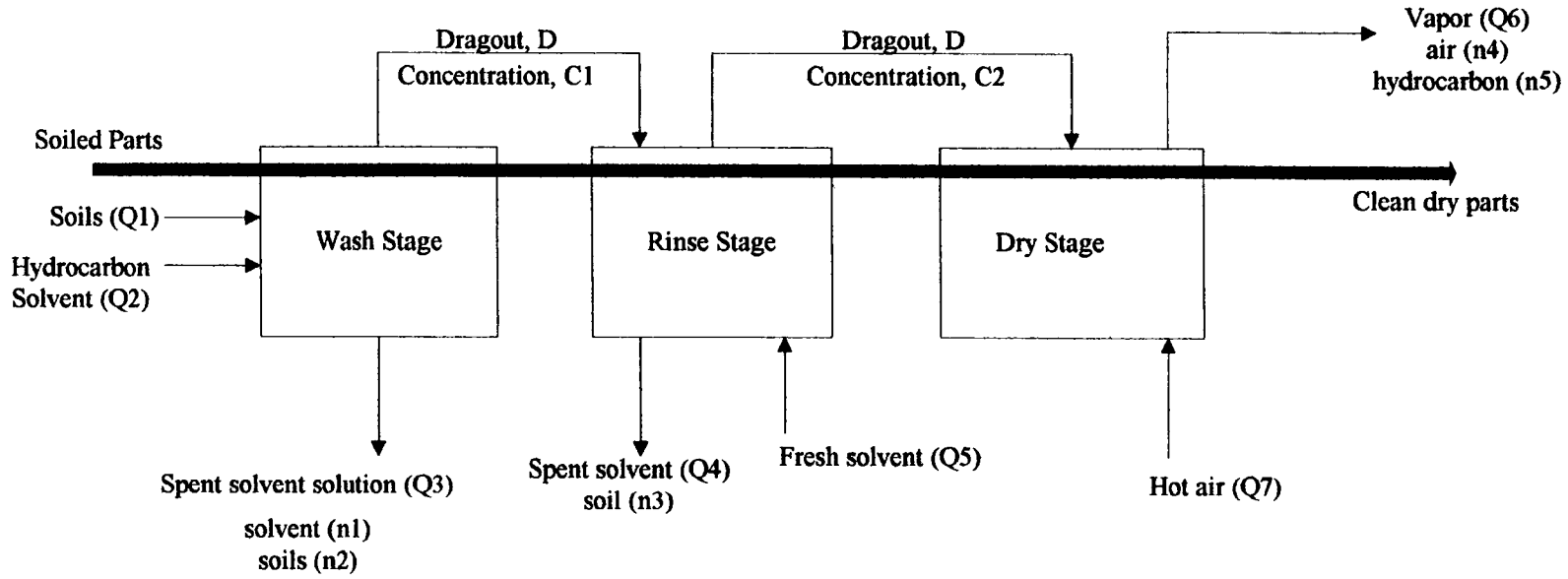

Figure 2.1.3 Hydrocarbon Process Flow Diagram

streams which will have to be dealt with for a particular alternative process. Input streams common to all three technologies shown in Figures 2.1.1, 2.1.2, and 2.1.3 include the work packages themselves accompanied by the soils. The soil is considered to be an intrinsic waste stream because it is independent of the cleaning process; the amounts of which remain the same for each alternative assuming no changes in the manufacturing operation. An aqueous process as shown in Figure 2.1.1 would produce three waste streams: spent cleaning solution (water, cleaner, soils), waste rinse water, and a water vapor stream from the drying stage. Of these streams only the first two are generally of concern. A semi-aqueous process (Figure 2.1.2) would also produce three waste streams: spent cleaning solvent (solvent, soils), waste rinse water (water, solvent), and a water vapor stream from the drying stage. As with aqueous cleaning, only the first two waste streams are generally of concern. A hydrocarbon process (Figure 2.1.3) would produce two waste streams: spent solvent (solvent, soil) and a solvent vapor stream from the drying stage. If the amounts of dragout (D) is limited to levels allowing for discharge of the rinse water directly to the publicly owned treatment works (POTW) then aqueous and semi-aqueous processes may only produce one waste stream of concern, the spent wash agent.

The cleanliness level desired of a new cleaning system is often the current level of cleanliness obtained with the vapor degreaser. This will require the determination of a cleanliness specification. Cleanliness specifications generally have two classifications, residual and process specifications. A residual specification is a characterization of the amounts of soil remaining on a surface (mg/ft^2) and is most employed in precision cleaning operations. A process specification characterizes cleanliness by the process used to clean the parts. In other words, if the part is cleaned with this wash agent in this process then it will be clean. This approach has been typical of non-precision metal parts

cleaning. The subsequent move to an alternative process however will require some establishment of a cleaning specification in which to compare the performance of the alternatives. Analytical techniques available to characterize the cleanliness levels of metal surfaces were the subject of investigation by Farella et al [2] and Sistla [3]. Spring has also discussed the methods available to determine cleanliness levels [4]. Commonly encountered analytical techniques include water-break, millipore, gravimetric, and UV tests. A testing procedure to compare alternative cleaning schemes was one of the first objectives in Pratt&Whitney's vapor degreaser replacement program [5]. The methods they selected to establish a cleanliness baseline were water break scoring and the measurement of residual weight on test panels. Philips Lighting initially considered UV, residual weight, and deionized water droplet tests to determine cleanliness levels [6]. Their final measure of cleanliness was determined using residual gas analysis. AT&T found photoemission spectroscopy to be best suited for determining cleanliness levels for their cleaning application [7]. The selection of an analytical technique will strongly depend upon the level of cleanliness required which in turn is strongly related to end use [4]. Cleanliness measurement and the subsequent determination of a cleaning specification can limit the choices among alternative processes or the final configuration of a given system.

For immersion equipment suitable for all three alternative technologies, equipment sizing depends primarily upon three characteristics of the manufacturing operation. These include the size and throughput of the work package, liquid volume displacement by the work package, the quantity (volume) of soil entering the immersion tank, and the soil loading in the tank that is desired to be maintained.

The work package size is the most apparent factor in immersion process vessel sizing. The work package makes reference to the part(s) placed at any one time in the

immersion tank to be cleaned. In other words, this is the number of parts per cleaning cycle. This depends strongly upon the production levels or the part throughput of the manufacturing process per unit time (P), and the cleaning process residence time per cleaning cycle (t). The number of parts per cleaning cycle can then be calculated from Equation (1).

$$\text{Parts/cleaning cycle} = (P)*(t) \qquad (1)$$

For instance, if it is desired to clean 300,000 small parts per day with a 20 minute cleaning cycle then the number of parts per cleaning cycle will be (300,000 parts/day)*(20 minutes/cleaning cycle) = 4,167 parts / cleaning cycle. The preceeding example used the conversion factor: 1 minute = 0.0006944 day. Once the number of parts per cleaning cycle has been calculated then the volume of that work package can be determined. This is a simple concept. A part with physical dimensions of one foot length, two feet width, and one foot height will require an immersion tank with at least a minimum of these same physical dimensions such that there is sufficient clearance between tank walls and the work package. This is also required of a work package consisting of multiple parts where the tank volume must accommodate the final stacking arrangement of the parts. In the preceeding example, 4,167 small parts per cleaning cycle were to be cleaned. The size of each part was estimated as 0.0285 in^3 or 119 in^3 per cleaning cycle [(4,167/cycle)*(0.0285 in^3)] or 0.52 gallons per cycle. Since this example uses small parts which will need to be placed into a perforated basket and rotated after their immersion into the cleaning medium, the volume of the work package will in this instance be the volume of the rotating basket. A basket size is selected which will allow for the tumbling of the parts when gently rotated. In this case, a volume for

the basket is selected which is 350 per cent of the volume of the parts per cleaning cycle or 1.8 gallons per cycle. In other words, the immersion tanks for this cleaning process must be at least 1.8 gallons. In production environments with variable work package sizes, immersion tanks must be sized to accommodate the largest work packages. Modifications for the cleaning of smaller work packages may then have to be made such as their placement in baskets.

Not only must the process tank accommodate the work package size but it must also account for displacement of the cleaner/solvent by the work package itself. In other words, an object will displace an amount of liquid equal to it's own volume when completely submerged. For instance, a work package estimated to be two gallons total in size will displace two gallons of liquid when fully submerged. Displacement must be accounted for because this will have the effect of raising the fluid level within the tank. In the preceeding example, the volume of parts was estimated to be 0.52 gallons. In this case this appears to be a negligble amount and probably is; however in the case of larger parts, the amount of fluid displaced and thus the rise in fluid level in the tank could be significantly more. Therefore, this must be an initial consideration in sizing immersion tanks.

The final, and in most instances the most significant consideration in sizing immersion tanks, is the amount of soil that enters the tank. The soil volume will only add to the overall volume of wash solution. This results in a raising of the fluid level of the tank. Soil volumes that are allowed to build up in the tank will depend upon how often the tank is changed out or vice versa; how often a tank is changed out will depend upon how much soil is allowed to build up in the tank. Both operating parameters are interdependent upon each other and will be closely related to the cleaner or solvents' soil

loading capabilities. This is often characterized as the ratio of soil to solvent by either volume or weight. This is shown represented in Equation (2) by volume.

$$\text{Soil Loading Fraction} = (\text{Soil Volume}) / (\text{Solvent Volume}) \qquad (2)$$

Typically, the soil volumes per cycle entering the process is known and the soil loading fraction to be maintained is estimated. This requires that the number of cleaning cycles per unit time of solvent change-out be determined (C) or the solvent volume of the tank per unit time of solvent change-out be calculated (S). The relationship that exists between these two factors can be seen in Equation (3).

$$S = [(\text{Soil per cleaning cycle}) * (C)] / (\text{Soil Loading Fraction}) \qquad (3)$$

If it is known what volume of solvent is preferred before a change-out is performed then the number of cleaning cycles which can be accommodated can be calculated. Also, if it is known what number of cleaning cycles is preferred before a change-out is performed then the solvent volume required to accommodate that number of cleaning cycles can be calculated. For example, if it is desired to maintain a soil volume of 30 per cent in a solvent immersion tank with a soil volume of 0.023 gallons per cycle entering the tank, 360 cleaning cycles per week, and it is desired to change-out the tank weekly then 27.6 gallons of solvent per cycle will be required. This means that the tank volume will have to be at least 27.6 gallons.

The immersion tank sizing considerations previously discussed were the size of the work package per cleaning cycle (WP/cycle), the displacement volume by the work package per cleaning cycle (Dp/cycle), the desired soil loading volumes or solvent

volumes per unit time of solvent/cleaner change-out (S/change-out), and soil amounts per unit time of solvent change-out (Soil/change-out). These are summed up by Equation (4). The significance of each consideration will vary per application.

$$\text{Tank Volume} = (\text{WP/cycle}) + (\text{Dp/cycle}) + (\text{S/change-out}) + (\text{Soil/change-out}) \quad (4)$$

Additional tank volume is recommended to allow for the liquid displacement due to the infrastructure associated with the mechanical means of agitation and with a possible parts basket. This additional tank volume will also guard against possible overflow in the event of process perturbations or upset. Typically, vendor recommendations can range from 20 to as much as 100 per cent of the calculated tank volume shown in Equation (1) [8]. However, additional tank volume means additional costs to the immersion tank. For the purpose of recognizing the need for an additional tank volume as well as the need to minimize tank costs, this thesis will recommend an additional tank volume of 25 per cent over that calculated in Equation (4). 25 per cent represents Springs' suggestion that the work packages themselves be not allowed to go beyond the bottom 25 per cent of the process tanks because this is where most tank sludge and debris can be expected to be found after cleaning [4]. Total recommended tank volume is now shown in Equation (5).

$$\text{Total Tank Volume} = 1.25\ (\text{Tank Volume}) \quad (5)$$

While all three process alternatives typically employ one wash stage, the number of rinse stages may vary considerably with application. Thorough rinsing is often a must for many cleaning applications and the extent of which can often only be determined by

testing. Although Mooney has stated that it will usually require more than two rinse tanks for an efficient recovery and rinsing process to be operated [9]. It has also been stated that rinsing is strongly enhanced by agitation within the rinse tank [9,10]. In finishing operations requiring a number of pre-treatment stages, good rinsing can be very important. The presence of wash residues has the potential to neutralize and undermine subsequent phosphating operations as was illustrated in cleaning studies conducted by AT&T in its' investigation of alternative wash agents [7]. Their general observation was that the more immiscible with water the wash agent was then the more difficult it was to rinse. In the precision cleaning arena, part cleanliness is often said to be a strong function of bath contamination [11]. Mohler has discussed the "contamination limit" of a rinse which demarcates a rinse concentration, above which no longer provides satisfactorily rinsed parts [10]. In processing schemes requiring a number of rinse stages, the arrangement most commonly encountered is a counter current cascade. This arrangement allows cleanliness levels of the parts to be estimated from the cleanliness level of the final rinse. In addition, a counter current rinse arrangement is the most prevalent waste minimization measure since it can significantly reduce the amounts of rinse required. Mooney has discussed the ideas behind water rinsing and has illustrated his discussion with the required calculations [9]. Mohler has presented similar calculations [10]. However the first rinse stage of a semi-aqueous process is referred to as an emulsion rinse and is not connected to subsequent rinse stages. This set-up allows for better separation and recycling of the wash agent through the use of a decanter due to the greater build up of soil contaminants in the emulsion tank. A decanter is often encountered in both aqueous and semi-aqueous cleaning and provides an easy method for separations to be performed. Figure 2.1.4 illustrates a semi-aqueous process with an

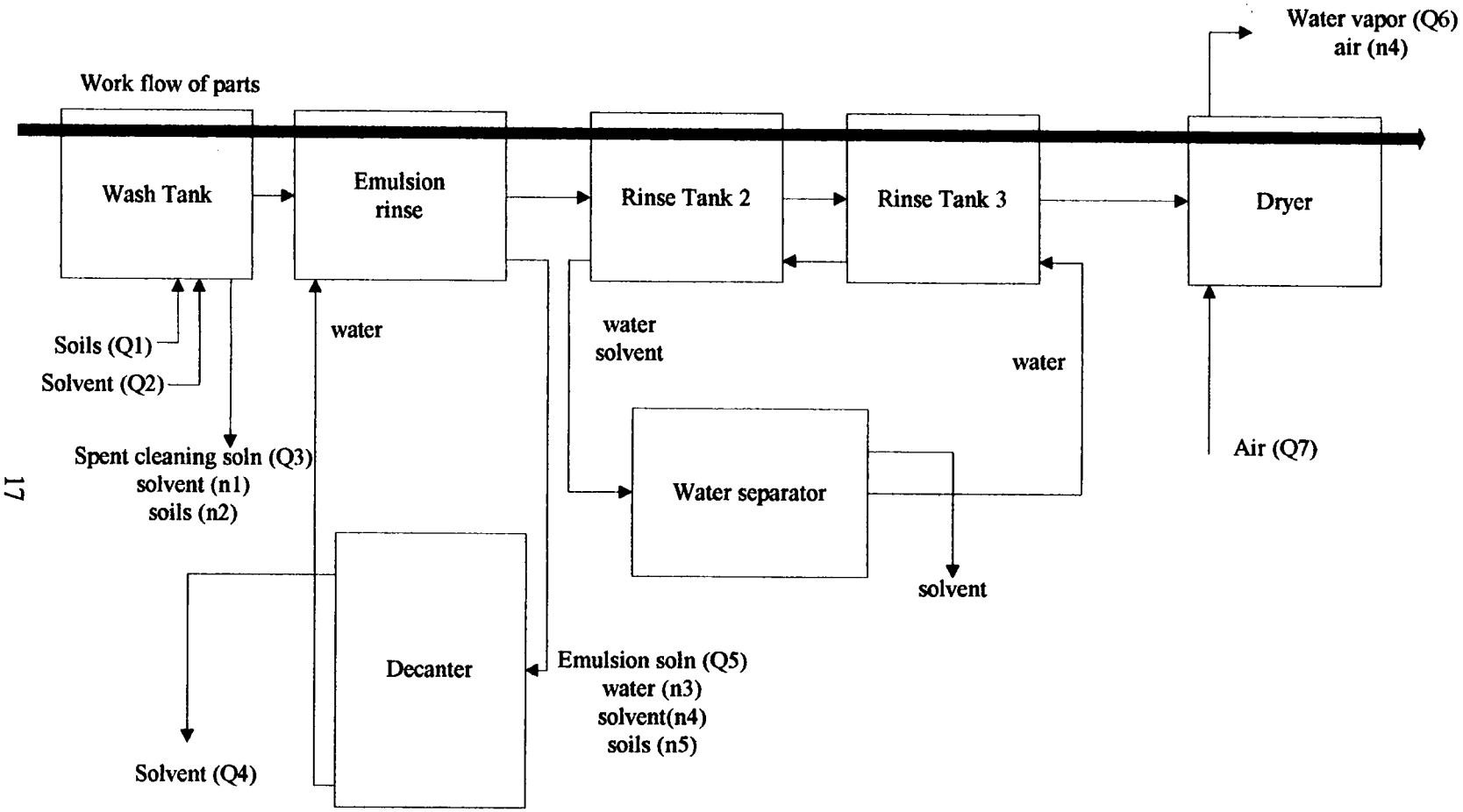

Figure 2.1.4 Advanced Semi-Aqueous Process Flow Diagram

emulsion rinse and two subsequent rinse stages. Immersion rinse tank sizing follows the same manner as presented for the wash tanks as given in Equations (1) through (5).

Another design consideration common to all three technologies is the phenomenon known as drag-out. This refers to the amounts of process fluid carried from one wash or rinse stage to the next. This may be the result of the orientation of the part as it passes through the cleaning process as well as from simple adhesion of the liquid to a parts' surface. This cross contamination is called the "drag-out". A part requiring a number of process stages must be oriented or "racked" so as to reduce the amounts of cross contamination from one stage to the next as it advances through the cleaning process. Sufficient time should also be allowed to permit the adhering liquid to drain back to the bulk fluid from the parts' surface. Minimizing drag-out can reduce the number of solution change-outs and the amounts of make-up cleaning solution or rinse required for a cleaning process. The significance of drag-out on a cleaning process was illustrated by AT&T in their studies of alternative wash agents [7]. They demonstrated that process drag-out contaminated a subsequent acid bath which in turn had a detrimental effect on their subsequent plating operation. They concluded that the primary cause of excess drag-out was their processing time. It was determined to be too fast to allow for adequate rinsing and reduced drag-out.

In general, rates of drag-out are related to the numbers and configurations of the parts being cleaned. Reductions in drag-out can sometimes be obtained by the slow removal of parts from solution to allow residual amounts of solution to drain back to the bulk solution. Further reductions may be obtained through the use of air knives to facilitate draining, the installation of drain boards, and by increasing solution temperature [12]. Mooney has suggested that orienting parts so that the low point is a corner rather than an edge will reduce the potential drag-out to one sixth as much otherwise [9].

Gruss has illustrated the potential amounts of drag-out that may be encountered for a number of part configurations based upon total surface area of a part [13]. These are shown in Table 2.1.2.

Table 2.1.2 Dragout Potentials

Part Type	Dragout, gallons/1000ft^2
Vertical parts, well drained	0.4
Vertical parts, poorly drained	2.0
Vertical parts, very poorly drained	4.0
Horizontal parts, well drained	0.8
Horizontal parts, very poorly drained	10.0
Cup shaped parts, very poorly drained	8 to 24 or more

A mathematical treatment of a mass balance around a theoretical cleaning process is presented in Appendix A. This example with two rinse stages illustrates the typical calculations that may be required. These equations may be used to calculate either the fresh rinse flow rate or dragout rate necessary to achieve a particular cleanliness level.

Soil loading is another process consideration which must be addressed for all three technologies. Soil loading refers to the amounts of soil which can be dissolved and held in solution by a solvent while still providing effective cleaning. In the case of aqueous cleaning, it refers to the amounts of soil which can be removed through mechanical means by a cleaner without interfering with any of the aqueous mechanisms of cleaning such as emulsification, saponification, or solubilization [14]. Soil loading can also be a very significant factor in sizing immersion tanks as was shown in Equation (4). Durkee has suggested that in the case of some hydrocarbons, terpenes and some

specialty cleaning chemicals, that for "superb" cleaning, only 1/10 of 1 per cent soil loading by volume is permissible [15]. For "adequate" cleaning, this level increases to only two to five per cent soil loading. These numbers translate into solvent volumes of 1000 to 20 to 50 times respectively the amounts of soil that is being cleaned. Of course, the descriptions of "superb" and "adequate" are subjective to interpretation and will vary per application and can only be determined quantitatively by actual testing. With aqueous cleaning, especially for particulates or petroleum based soil contaminants, soil loading may not be as significant a factor due to the general ease of separations. This allows the water to be recycled in the cleaning process. However, time for these separations to occur must be allowed. In addition, the amounts of soil allowed to build up in the bottom of the tank cannot be ignored when sizing.

In the case of batch cabinet spray equipment, sizing depends only upon the work package size. Spray equipment is less effective when the nozzles are further from the work package itself. Therefore, too large of a spray chamber may mitigate the effectiveness of the sprays to clean. Testing is once again recommended for a particular application. For continuous conveyorized spray equipment, the rate at which the parts are conveyed through the process will also have an effect on the size. For instance a part on a conveyor moving at 10 meters per minute and requiring a minimum of 20 seconds exposure in the wash will require a spray chamber with a fixed length of 3.3 meters. In addition, the amounts of soil entering the cleaning process can be a factor in spray equipment sizing and must be accounted for in reservoir volume. This also speaks to soil loading. For batch processing spray equipment, drag-out is not a primary concern. However for continuous spray equipment with work packages transferred through the process by conveyor or belt, drag-out can have a detrimental effect on bath life. As with

immersion equipment, the primary consideration is part orientation and speed through the process.

Complete energy balances on cleaning systems will depend strongly upon the equipment selected. The following discussion considers the energy requirements of alternative processes with the exception of the drying stage. Drying, while an important component of alternative processes, will be considered a separate manufacturing operation and is not covered in this thesis.

The cleaning agents possess physical properties which suggest possible energy requirements. The amount of energy required to heat a volume of liquid from one temperature to another is directly proportional to the mass of the liquid and its' heat capacity. This is shown as Equation (3).

$$Q = m\, C_p\, \Delta T \qquad (3)$$

The heat capacities of several wash agents are shown in Table 2.1.3 [16,17].

Aqueous cleaning is almost always done at elevated temperatures. Temperatures of 140 °F - 160 °F are typically recommended for optimum cleaning. Thompson states that researchers at Oak Ridge National Labs have determined in the case of aqueous cleaning that a temperature of 55 °C (131 °F) was typically effective [18]. Von Steeg cites a case study in which an aqueous system with operating temperatures of 71 °C (160 °F) for ferrous metals and 60 °C (140 °F) for aluminum was found to be optimum [19]. However, the heating of the aqueous wash solution does contribute significantly to the cost of aqueous cleaning. In the case of terpenes and hydrocarbons, ambient temperatures are often recommended to reduce the fire hazard associated with their use

Table 2.1.3 Wash Agent Heat Capacities

Wash Agent	Temperature	Heat Capacity (C_p)
water	0°C≤T≤71°C	$4.225<C_p$(kJ/kg·°C)<4.186
terpenes[1]	0°C	1.84 kJ/kg·°C
NMP	25°C	3.11 kJ/kg·°C
DBE[2]	20°C	1.78 kJ/kg·°C
hydrocarbons[1]	0°C	1.90 kJ/kg·°C
glycol ether		
diethylene glycol	25°C	2.3 kJ/kg·°C
diethylene glycol dimethyl ether	25°C	3.7 kJ/kg·°C

[1] Method of Johnson and Huang [17]

[2] Method of Gambill [17]

in cleaning operations. NMP, DBE, and glycol ethers can be heated in cleaning applications to improve cleaning efficiency.

Typically, metal parts being cleaned will carry out more heat from a cleaning process than non-metals. The physical properties of metals which may suggest how much heat is lost from a cleaning process are thermal conductivity (k) and heat capacity (c_p). Both properties are functions of temperature; how much so is dependent upon the metal itself and its' molecular structure.

Thermal conductivity is a transport property of a material. It is in general, strongly temperature dependent. The thermal conductivity proportionality constant (k) is a measure of the heat rate or how quickly heat is conducted through the material. In general, metals have high thermal conductivity constants. Table 2.1.4 lists the thermal conductivity constants for several common metals encountered in manufacturing operations [16,20]. It also lists for comparison the thermal conductivity constants of other media. The conductivities listed are for the temperatures shown.

Heat capacity, a physical property of a material; is a measure of that materials' ability to retain heat. More specifically it is the amount of heat required to raise the temperature of the material 1 degree. This property is also strongly temperature dependent. Materials with high heat capacities can retain higher amounts of heat absorbed from a process. Table 2.1.5 provides a list of heat capacities of common metals. It also lists for comparison the heat capacities of other media [16,20]. The heat capacities listed are for the temperatures shown.

In a metal cleaning process, the properties of thermal conductivity and heat capacity typically mean that heat will be lost from the process; carried out by the metal parts being cleaned. This can be exploited in some aqueous processes. Parts washed at elevated aqueous temperatures will "flash" dry when removed from the process due to

Table 2.1.4 Thermal Conductivities

Materials	Temperature		Heat Conductivity	
	(°F)	(°C)	(W/m·°C)	(Btu/hr·ft·°F)
brass (70% Cu, 30% Zn)	68	20	111	64
aluminum (pure)	68	20	204	118
lead	68	20	35	20
iron (pure)	68	20	73	42
carbon steel (C=1%)	68	20	43	25
copper (pure)	68	20	386	223
tin (pure)	68	20	64	37
window glass	68	20	0.78	0.45
polycarbonate	68	20	0.20	0.12
polyethylene (low density)	68	20	0.34	0.20

Table 2.1.5 Material Heat Capacities

Materials	Temperature		Heat Capacity	
	(°F)	(°C)	(kJ/kg·°C)	(Btu/lb_m·°F)
brass (70% Cu, 30% Zn)	68	20	0.385	0.092
aluminum (pure)	68	20	0.896	0.214
lead	68	20	0.130	0.031
iron (pure)	68	20	0.452	0.108
carbon steel (C=1%)	68	20	0.473	0.113
copper (pure)	68	20	0.383	0.091
tin (pure)	68	20	0.227	0.054
window glass	68	20	0.840	0.201
polycarbonate	68	20	1.26	0.300
polyethylene (low density)	68	20	2.30	0.549

their own elevated temperatures. Generally though, heat losses are generally of concern with aqueous cleaning processes only.

A heat balance around a cleaning process is summarized in Equation (4). All components of the heat balance may not be significant for all cleaning processes.

Heat loss = (initial heat to raise temp. of wash agent) - (heat carried out by parts) - (conductive heat lost through tank walls) - (latent heat of vaporization losses) - (convective heat lost to air) (4)

An energy balance around a cleaning process may be summarized by Equation (5). All components of the heat balance may not be significant in all cleaning processes.

Energy req'd = (initial energy to heat) + (energy to maintain temperature/make-up energy for heat losses) + (equipment energy requirements) (5)

2.2 Alternative Cleaning Processes

This thesis will consider three alternative industrial cleaning technologies to replace traditional vapor degreasing with chlorinated chemicals. The three technology alternatives will be classified as aqueous, semi-aqueous, and hydrocarbon immersion cleaning; with each classification making reference to the type of wash and rinse agents utilized in the process. Each of these alternatives have been the subject of discussion in varying detail in other literature [21].

Manufacturing and cleaning process considerations such as part throughput, level of cleanliness desired, part configuration, and type of metal substrate and its' sensitivities

can effect the selection of both the mechanical agitation and wash agent of an alternative cleaning process. Process considerations such as these have been the subject of investigation and analysis by several sources in attempts to clarify the significance of each on the selection of an alternative cleaning process. The Solvent Alternatives GuidE (SAGE) developed by the EPA is an interactive computer program that has weighted such process factors and depending upon the answers selected, suggests possible cleaning alternative agents and processes [22]. A comparison of SAGE predictions and actual laboratory testing of alternative wash agents and processes was the subject of investigation by Stafford who found favorable comparison between the two [23]. Petroferm, Inc. has developed it's own decision tree with questions concerning the cleaning process as branches which terminate in possible alternative cleaning processes. [24]. A similar decision tree was proposed by English [25]. A decision tree developed by Durkee to help in the selection of an alternative cleaning process goes one step further than the decision trees aforementioned [15]. Instead of suggesting an alternative cleaning process, Durkee's decision tree terminates in 12 common alternative cleaning solutions complete with a suggested number of cleaning stages. This approach has the benefit of better illustrating for the user the components that will comprise an alternative cleaning process. Although dated 1974, prior to regulations regarding chlorinated solvents, Snogren developed a Method Selection Guide for cleaning processes based upon the substrate being cleaned and the post-treatment which follows [26]. This methodology serves to illustrate the levels of cleanliness typically achieved with various cleaning methods based upon the subsequent quality of coating which is achieved. A similar methodology for selecting a cleaning process was proposed by the ASM Committee on "Selection of A Cleaning Process" [27].

Generally in the cleaning process industry, aqueous wash agents are referred to as cleaners and organic wash agents are classified as solvents. The following discussion uses this convention in providing a brief overview of the three available alternative processes considered in this thesis for selection as industrial cleaning processes. The solvents mentioned are restricted to a few select solvent chemistries which have been suggested as possible cleaning substitutes for halogenated solvents by the Environmental Protection Agency (EPA) under the Significant New Alternatives Policy (SNAP) program [28]. They are identified as having a minimal impact on the environment when compared to chlorinated solvents and as being commercially viable solvent alternatives in terms of availability, practicality, and cost for all sizes of manufacturers of metal parts.

The successful selection of an alternative industrial cleaning process for metal parts is primarily dependent upon the selected wash agent. Wash agents are used to remove soil contamination from the surface of a part. The main consideration in the selection of the wash agent is whether the soil contaminant will be soluble. This requires that the soils to be removed be characterized early in the alternative cleaning process planning when defining the cleaning problem as was done by Pratt&Whitney and AT&T in their evaluation of alternative wash agents [5,7].

The heuristic "likes dissolves likes" often provides sufficient guidance as to which type of wash agent may be appropriate for a particular soil contaminant. The removal of the soil contaminant can be accomplished either by mechanical displacement or by dissolving it in the wash agent. However most industrial cleaning processes utilize a combination of both approaches. In the case where chemical solvency is not important such as solid particle removal, then cleaning will involve the selection of a medium to serve as the mechanical means of particle removal. In these instances, water is most often the recommended cleaning medium.

However just satisfying the "likes dissolves likes" criteria may not be satisfactory enough to provide the level of cleanliness sought. The effectiveness of an aqueous cleaner or solvent can depend upon wash agent concentration, type of mechanical agitation, temperature, and wash residence time. In one study, the cleaning capabilities of a given cleaner were stated to depend more favorably on thermal energy (temperature), then on chemical energy (concentration) and mechanical energy (agitation) [29]. The significance of temperature on the effectiveness of a cleaning agent was also the finding of Stafford in optimization studies done in support of SAGE [23]. To examine the impact of these parameters further on cleanliness, the concentration and temperature operating parameters of an aqueous cleaning process was thoroughly investigated by General Dynamics during their search for a replacement to halogenated solvent degreasers [30]. A variety of commercial cleaners having an alkaline chemistry were used to clean aluminum coupons (small square pieces of the metal representative of a larger aluminum part) over a range of operating temperatures and concentrations. This allowed a complete concentration-temperature profile to be obtained for each cleaner's measured effectiveness. Test results showed that temperature was indeed more significant on the cleanliness level achieved for the metal coupons than concentration and that under operating conditions with elevated temperatures, aqueous alkaline cleaning was effective in removing a variety of non-polar soil contaminates. It should be cautioned however that different soil contaminants will most likely require different operating parameters to achieve maximum removal efficiency. It has been suggested that some soils may even become set at higher temperatures and concentrations [12]. Spring has stated that for aqueous cleaners, a general rule is that only slight or no improvement in cleanliness is usually the case with concentrations greater than 12 ounces per gallon [4]. Thus successful cleaning may require a lower temperature, concentration, and

longer wash residence time than may have been thought. In tests performed by Pratt&Whitney, it was suggested that the largest factor with an impact on cleaning was the equipment followed by the type of wash agent and concentration [5]. Soil loading, time, and temperature were determined to each have equivalent minimal impacts on the cleanliness levels obtained. These studies emphasize the point that generalizations for parts cleaning are difficult to make and the testing of actual parts for various cleaners and solvents under different operating conditions is highly recommended and very often required.

According to Sprow, the EPA has ascertained that one fifth of all cleaning can be accomplished only with solvents and another fifth only with aqueous cleaning. The remaining three fifths of all cleaning applications can go either way [31]. It is in this final category that most metal cleaning applications will be found.

The EPA has compiled lists of alternative wash agent vendors according to the type of wash agent [28]. Carter has compiled a similar listing [32]. Precision Cleaning Magazine also has an annual wash agent directory which lists more than a 100 companies involved in the manufacture of industrial wash agents [33].

2.2.1 Aqueous cleaning

Due to public and industrial anxiety about solvent usage and governmental regulation of its' disposal; aqueous cleaning is often the preferred technology for industrial cleaning in manufacturing operations. As of June 1989, aqueous cleaning was said to be employed in 38 per cent of the world production of printed circuit boards (PCB's) [34]. Furthermore, D'Ruiz approximates that 80 to 90 per cent of all metal cleaning and degreasing applications and 90 per cent of all non-surface mount electronics and assembly cleaning applications may be viable candidates for aqueous cleaning processes [35]. In addition, following thorough testing, General Dynamics identified

three aqueous cleaners which out performed chlorinated vapor degreasing [30]. However, it is not the panacea for all cleaning applications, especially metal parts, and often requires considerably more testing and optimization than the other cleaning alternatives discussed in this thesis.

Aqueous cleaning processes use water as the primary medium in which to wash parts. Pure water alone has limited capabilities as a parts cleaner when no mechanical agitation is utilized. However in the case where the soil contaminant is ionic in nature such as inorganic salts, pure water as the cleaning medium can be used. This is due to the nature of the intermolecular forces which bind the water molecules together and the type of bonding which binds the atoms of the inorganic soil contaminants together. However in industrial parts cleaning very few soils are of this nature and thus a mechanical means must be used with water to displace the soil from the part. The use of water alone in a spray system was investigated by NASA for the removal of soil contamination from the network of piping which make up the space shuttle launch process at the Kennedy Space Center [36]. The problem with using water is the limited solubility of the usually encountered soil contaminants. Utilizing a simple experimental method, NASA researchers demonstrated that pure water was not an effective cleaner of organic soil contaminants such as oils and greases for their application with removal efficiencies ranging from 2 per cent to 100 per cent; depending heavily upon the type of soil contaminant. Although in applications involving solid particle removal and no chemical solvency; water can be an excellent cleaning medium.

To improve the cleaning performance of water, it is often necessary to use a solution with various chemical additives. The available literature offers different classifications of these additives but for this discussion they will be classified as described in the definition of aqueous cleaning offered by the Society of Manufacturing Engineers.

They described aqueous cleaning as a solution of water, detergents, surfactants, and builders used to release soils from machined parts. Each of these chemical additives addresses a problem encountered in aqueous cleaning by performing a specific function to assist in the removal of the soil contaminant and gives rise to the categorization of aqueous cleaning as alkaline, acidic, and neutral aqueous cleaning with alkaline cleaning gaining the most acceptance in the industry. However acidic cleaning promotes the brightening of most metals, often a desired trait while neutral cleaning generally offers the best employee handling with regards to safety and reduced environmental liability since it doesn't require neutralizing before discharge.

Each of the chemical additives present in a cleaner is there to address a problem encountered with aqueous cleaning. For example, surfactants decrease the surface tension of water at the part/surface interface thereby increasing the wetting of the parts' surface by the aqueous solution [37]. The increased wetting enables the cleaning solution to penetrate blind holes and small surface irregularities more easily. Surfactants also increase the solubility of many hydrocarbon soil contaminants as well, through the process of emulsification. Surfactants are commonly categorized as anionic, nonionic, cationic, and amphoteric depending upon the nature of the polar component of the surfactant molecule. This quality often gives partial rise to the nature of the aqueous cleaning solution being categorized as acidic, basic, or neutral. Typical surfactants encountered in aqueous detergent formulations include sodium alkylbenzene sulfonates and quaternary ammonium chlorides. Further information on surfactant systems can be obtained from Evans and Wennerstrom [38].

Rust inhibitors are very significant components of an aqueous cleaner. They are added to address the problem of "rusting" or corrosion of carbon based metal surfaces. Rust is the oxidation of a metal, especially ferrous metals, as a result of contact with

water. Inhibitors work by forming a protective film on the surface of a metal part that either excludes oxygen or reacts with it before the metal can oxidize. This chemical phenomenon is known as passivation. The importance of rust control for an aqueous cleaning process for metal parts and the problems associated with it are illustrated in a case study involving Means Industries, Inc. [39]. Means Industries had switched from a mineral spirits rust inhibitor when they made the switch to an aqueous cleaning system. Their aqueous cleaner had a rust inhibitor formulated into it. It provided the desired level of protection but, as was discovered, necessitated much tighter control over it's concentration in the cleaner and during the subsequent drying step. A year long monitoring of the cleaner and parts demonstrated that the atmospheric conditions of humidity and temperature at which drying took place had an effect on the quality of rust protection obtained for the parts. It was discovered that a 4 per cent inhibitor concentration was adequate for the cooler months from October to May while the warmer months required an 8 per cent inhibitor concentration. Von Steeg cites a case study in which a rust inhibitor concentration of 25 per cent by volume was necessary to provide up to eight weeks of corrosion protection following cleaning [19]. General Dynamics also discovered during their evaluation studies of alternative wash agents that some of their metal substrates were highly susceptible to oxidation when aqueous cleaning was applied [30]. Common rust inhibiting chemical agents include sodium metasilicate and sodium orthosilicate. These agents are known to be difficult to rinse and may contribute to problems in subsequent finishing operations if they are not adequately removed during rinsing [27].

The quality of the water used in the aqueous cleaning of metal parts cannot be taken for granted. Common tap water contains trace minerals such as magnesium, calcium and iron. This is often referred to as "hard water". Hard water can hinder a

cleaners' effectiveness of by forming insoluble products with the various other chemical additives present in the cleaner. As a result, the efficiency of the cleaning solution as well as the level of cleanliness of the parts can diminish. The most common example used to illustrate this effect is the hard water scale or scum that is formed in sink and tub basins. This scale is the result of a reaction between the metal cations in water and soap detergent. To prevent this scale from forming the water will need to be treated. The extent of this treatment can range from simple water softening systems to complex water de-ionizing systems [40]. Costs of water treatment can vary considerably with the method selected. One method of chemical treatment of ordinary water often encountered in metal parts cleaning is with the use of chelating compounds. These can often be formulated into a cleaner. In this process, chelating compounds are used as sequestering agents to "tie-up" the metal cations by forming very stable and water soluble complexes with them. Common sequestering agents used in water softening are polyphosphates and ethylene-diaminetetraacetates such as trisodium nitrilotriacetate (NTA) and tetrasodium ethylenediamine tetraacetate (EDTA). These sequestering agents are members of a class of compounds called chelating agents. Chelating agents are a broad class of chemicals noted for their ability to form very stable complexes with metal ions. The word chelate was derived from the Greek and means "crabs claw". The term sequestering agent refers to how the chelating agent is used. In this case the metal ions present in tap water are sequestered or "tied-up" in a soluble complex to alleviate any problems associated with their presence without the necessity of removing them from the solution. Regardless of the approach to water treatment, aqueous cleaning will almost always require it. When it is necessary to be installed, de-ionized water will provide the highest water quality for processing. The fundamentals of water de-ionization have been discussed by Hirsch [41].

"Builders" makes reference to a variety of other chemical agents added to aqueous detergent formulations to act as pH buffers, water softeners, and provide additional cleaner or surface enhancement. Common builders include borates and carbonates.

It should be noted however that the use of chemical additives found in aqueous cleaners are not without their drawbacks. In the case of an alkaline chemistry, the alkalinity may be effected by the acidity of the soil contaminant, carbon dioxide present in air introduced to the system through agitation, and the use of sequestering agents in the cleaning solution. It has been suggested that 10-25 per cent of the cleaner may be consumed due to the use of sequestering agents alone [12]. Furthermore, some metals may react with some cleaners' active ingredients. For example, in alkaline solutions using sodium hydroxide, the hydroxyl group (OH) will attack aluminum and stain brass and copper alloys [42]. In aqueous systems considerable engineering, experimentation, and optimization is often required to deliver the performance required.

A block diagram representative of an aqueous process was shown in Figure 2.1.1 which illustrated that water is used as both the wash and rinse agent. The EPA currently lists approximately 40 specialty chemical vendors involved in the production of aqueous cleaners for both precision and general metal cleaning [28]. These companies combine to produce some 200+ aqueous detergent formulations for the industrial metal parts cleaning industry. However daunting the selection of an aqueous cleaning agent may appear to be, the fact is that 80 per cent of the actual cleaning using aqueous technologies is attributable to the mechanical means of cleaning with the remaining 20 per cent due to the detergent formulation [43]. This fact would seem to suggest that in the case of aqueous cleaning it would be more wise to concentrate on the handling of the part being washed and the equipment selected. Waste minimization measures applicable

to aqueous cleaning were the subject of investigation by the EPA [12]. Equipment suitable for aqueous cleaning will be addressed in section 2.3 of this thesis.

2.2.2 Semi-aqueous cleaning

Semi-aqueous cleaning processes were the subject of discussion by Merchant et al [31,44,45,46]. A semi-aqueous cleaning process is one which utilizes an organic solvent in the wash stage and water in the rinse(s) stage. In this scheme, the solvent is used to remove a hydrocarbon based soil contaminant and the water removes residual solvent and any ionic soil contaminants. This requires that the parts must be compatible with water. A flow diagram of a semi-aqueous process was shown in Figure 2.1.2.

Semi-aqueous cleaning was primarily pioneered as an industrial cleaning alternative in the mid 1980's [44]. Hayes suggested in 1990 that it was the leading alternative for replacing CFC's in electronics assembly cleaning [44]. This technology was originally intended to use a water immiscible solvent to wash the parts followed by a water rinse. This allowed for the economic separation and recycling of the rinse water. However water miscible agents are now commonly encountered in semi-aqueous cleaning as well. Organic solvents representative of many chemistries have been used in semi-aqueous cleaning. They are terpenes, aliphatic hydrocarbons, dibasic esters, and N-methyl2-pyrrolidone, and ethyl glycols. Originally semi-aqueous solvents were known as emulsion cleaners in the metal cleaning industry [21]. In this process, the selection of the wash agent is of paramount importance. It must be compatible with both the soil contaminant and substrate. Some plastics may be dissolved by semi-aqueous wash agents under certain operating conditions. However, semi-aqueous cleaning technology is said to deliver highest levels of cleaning performance than other alternatives [45]. This is because of the higher solubility of hydrocarbon base soil contaminants in the wash agents and the water rinse which is intended to wash away any wash agent residues or

ionic soil contaminants remaining on the parts' surface. In tests performed by AT&T, the semi-aqueous wash agents terpenes, aliphatic hydrocarbons, and esters generally out performed aqueous cleaners [7]. They concluded that for their cleaning application, an ester showed the most promise and was thus selected for trial testing in production. Similar results concerning the effectiveness of terpenes and esters were reported by Ray et al to clean electronic components [47].

The solvents, chiefly terpenes and hydrocarbon blends may also include non-ionic surfactant formulations designed to enhance their cleaning properties. Dishart has described the formulation of one such semi-aqueous agent, Axarel 32, as containing three different components: an aliphatic hydrocarbon, a dibasic ester, and a nonionic surfactant [48]. However, terpene wash agents have emerged as the leading semi-aqueous wash agent. The bath life for terpenes has been reported as a limiting factor in terpene use as a cleaning medium due to the exposure to oxygen in the air over time [48]. Environmental, health, and safety aspects of terpene wash agents used in the manufacture of PCB's were discussed by Ellis who concluded that odor may be the worst aspect associated with their use [34]. Chelating agents or rust inhibitors may be added to the rinse water depending upon the quality of the water being used. As with aqueous cleaning, de-ionized water is preferred thereby negating the use of chelating chemicals.

Hayes has suggested that the volume of semi-aqueous solvent which will be required to clean in most applications will be substantially less than the volume of halogenated solvent required to perform the same cleaning chore [44]. Merchant has stated that the high soil loading capabilities of semi-aqueous wash agents is responsible for this reduction in consumption of wash agent for many cleaning applications [45]. Koelsch has stated the soil loading of semi-aqueous wash agents is significantly higher than aqueous cleaners as well [42]. Furthermore, it has been stated that semi-aqueous

wash agents typically phase separate from water at concentrations above 2 per cent [49]. This feature greatly facilitates subsequent separations. Waste minimization techniques for semi-aqueous cleaning processes was the subject of discussion by the EPA [12].

Merchant suggests that for semi-aqueous cleaning processes with minimal dragout from the wash tank to the rinse tank that it may be possible to dispose of the final rinse by simply putting it down the drain [45]. However difficulty with rinsing some of the aliphatic hydrocarbons and ester wash agents from parts was encountered by AT&T in tests designed to evaluate alternative wash agents [7].

2.2.3 Hydrocarbon immersion cleaning

Hydrocarbon immersion cleaning utilizes terpenes or an aliphatic hydrocarbon as both wash and rinse agent. This cleaning is often used to replace chlorinated solvents in many industrial operations. It offers high solubility of contaminants such as waxes, oils, greases, and other petroleum based soils and can provide a thin layer of rust protection for the short term following cleaning. This is due to residues which may remain long after they are cleaned [21]. A flow diagram of a hydrocarbon immersion process was shown in Figure 2.1.3. Typically, the immersion tanks of a hydrocarbon process are connected in series which allow for cascade flow of solvent from the last rinse tank to the wash tank. With this arrangement, the level of cleanliness is said to be defined by the soil contaminant level of the final rinse [45]. However, in general, the level of cleanliness obtained is not as high as with the other alternatives.

The hydrocarbons in use today are designed for higher performance than the mineral spirit hydrocarbons of decades ago. They have undergone hydrogenation. This process removes all aromatic components of a hydrocarbon feed stock as well as many double and triple bonds. Generally the hydrocarbons marketed towards the metal cleaning industry today are blends containing oxygenated hydrocarbons [42]. The effect

of this is to increase the flash point of the agent by reducing the volatility. This is also said to reduce the odor of these wash agents [42]. Furthermore these latest hydrocarbons can be disposed of often as simple ignitable waste with a fuel value. Merchant has suggested that the cleaning performance of hydrocarbon wash agents at ambient or elevated temperatures in many cases can equal or exceed the cleaning performance of TCA [45]. Elevated temperatures are often required to clean high-melting waxes and grease. However the hydrocarbon wash agent should have a high enough flash point to allow for heating. A low flash point is said to be the primary safety issue related to their use. A general recommendation is to keep the operating temperature at least 17 degrees Celcius below the flash point of the solvent [42]. The hydrocarbon solvents may also include non-ionic surfactant packages similar to that mentioned for the aqueous and semi-aqueous technologies to enhance their cleaning performance.

Possible waste minimization techniques applicable for hydrocarbon cleaning were discussed by the EPA [12].

2.3 Alternative Cleaning Process Equipment

The wash agent and equipment are inherently related in their selection and in the performance of the cleaning operation as a whole. As previously stated, 80 per cent of the cleaning in an aqueous process can be attributed to the mechanical force introduced between the parts being cleaned and the cleaner [43]. In solvent systems, the percentage of cleaning attributable to mechanical means is roughly 20 per cent. Furthermore, it was suggested in one study that the type of equipment had the largest impact on cleanliness levels obtained with any alternative cleaning process [5]. The implication for alternative

cleaning processes is that equipment selection will have a significant impact on the levels of cleanliness obtained.

Generally, the wash chemistry will for the most part dictate the type of equipment selected. Almost all equipment configurations are basically immersion or spray mechanisms or combinations thereof. Immersion equipment is suitable for use with all three alternative processes previously discussed while open air spray equipment is primarily used with aqueous processing.

The EPA has compiled a vendor list of industrial cleaning equipment manufacturers as part of its' SNAP policy [28]. Carter has compiled a similar listing [32]. Precision Cleaning Magazine has an annual cleaning equipment directory issue which lists more than 125 vendors of cleaning equipment [50].

2.3.1 Spray Equipment

The most common equipment configuration for aqueous cleaning utilizes impingement or spray washing. In a spray wash process, an aqueous cleaning solution containing water and a cleaner, are contacted with the soiled part through forced impingment of the parts' surface. Impingment is the result of the cleaning solution being forced from a number of nozzles located in a piping manifold under pressure of a circulating pump. This necessitates a cleaner with low-foaming characteristics which are generally regarded to not clean as well as higher foaming cleaners used in aqueous immersion cleaning. This fact emphasizes the need for an efficient impingement process. Typically spray applications are categorized as high and low pressure with sprays operating below 300 psi considered low pressure. Spring has stated that spray pressures are generally measured at the entrance to the pipe and that the distance of the spray from the work package and the geometry of the piping will determine the pressure drop and thus the efficiency of impingement [4]. A design hueristic which can offer some

guidance as to the appropriateness of an open air spray washing is "the spray won't clean what it can't see" [43]. This makes reference to the geometry of the surface to be cleaned. Spring has suggested that processing times for spray systems could be only 20 per cent of those required for immersion cleaning processes [4]. Figures 2.3.1 and 2.3.2 are representative schematics of typical spray equipment configurations.

Figure 2.3.1 (a) and (b) offers two equipment variations of a continuous open air spray washer. In the configuration shown in Figure 2.3.1(a), individual parts are hung from racks attached to an overhead conveyor as they proceed through the wash process. The residence time through the wash process required to obtain optimum cleaning is determined from testing and is controlled by the speed of the conveyor system. Figure 2.3.1(b) is similar to Figure 2.3.1(a) but in this case the parts proceed through the wash process placed on a belt conveyor. Typically the equipment shown in Figures 2.3.1 is encountered in manufacturing operations characterized by large steady production volumes of medium to large, geometrically uncomplicated parts.

Figures 2.3.2 (a) and 2.3.2 (b) are referred to as rotary batch spray washers or batch cabinet spray washers [51]. In this open air spray configuration, the parts are placed on a support grid which rotates while the parts are exposed to the spray. Figure 2.3.2 (a) is referred to as a top-load cabinet spray washer while 2.3.2 (b) is a front-load cabinet spray washer. In both equipment configurations of Figures 2.3.1 and 2.3.2, the number of reservoirs is equivalent to the number of stages of the cleaning process. Thus for a cleaning process which requires a number of cleaning stages such as wash, rinse, and rust inhibitor, an open air continuous spray system may be more a more suitable selection while the batch spray system would be more suitable for single stage cleaning applications consisting of a wash stage only. In general the rotary spray washer may take up less floor space than an open air spray process designed for linear flow of the

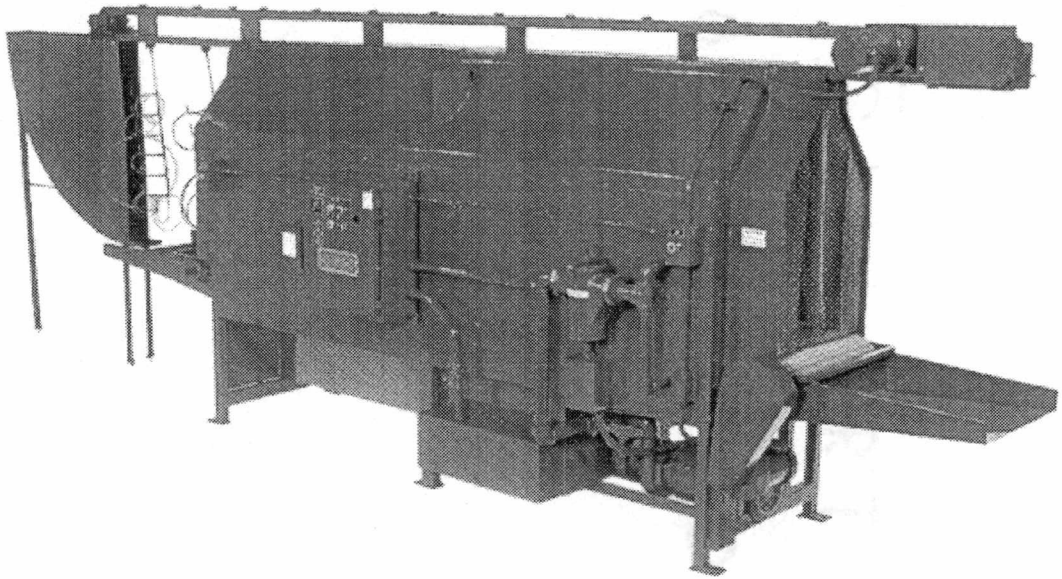

Figure 2.3.1 (a) Overhead Conveyor Continuous Spray Washer

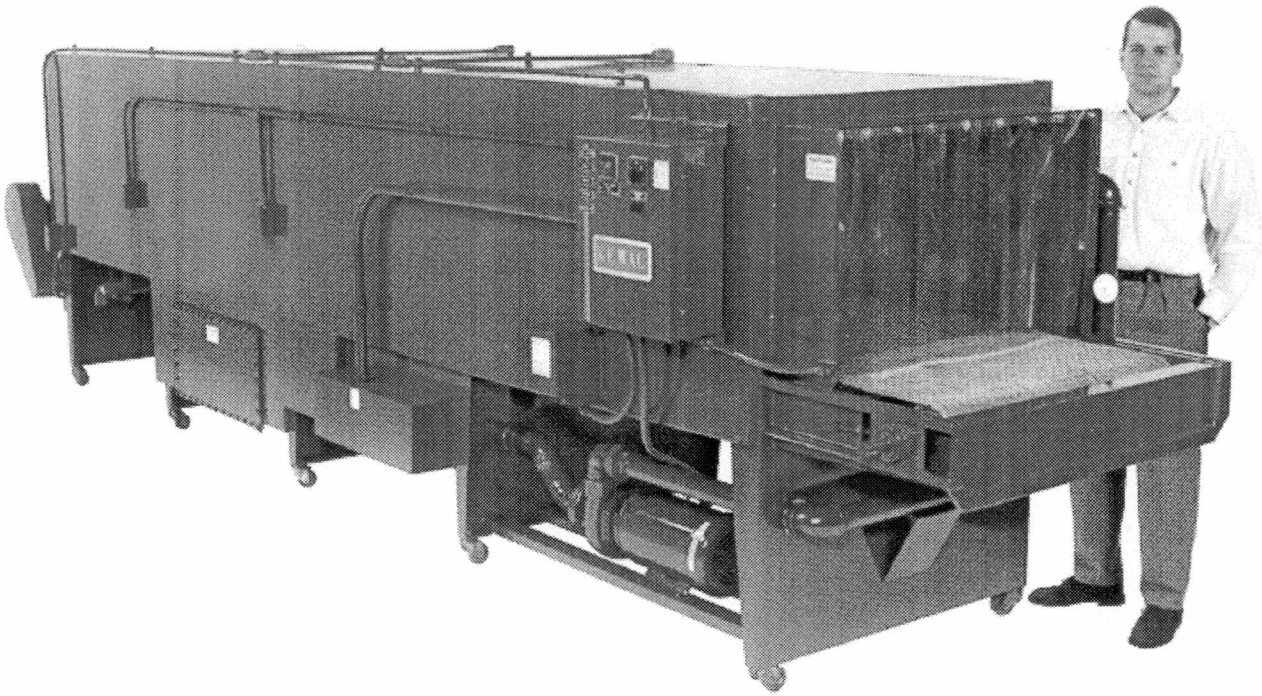

Figure 2.3.1 (b) Belt Conveyor Continuous Spray Washer

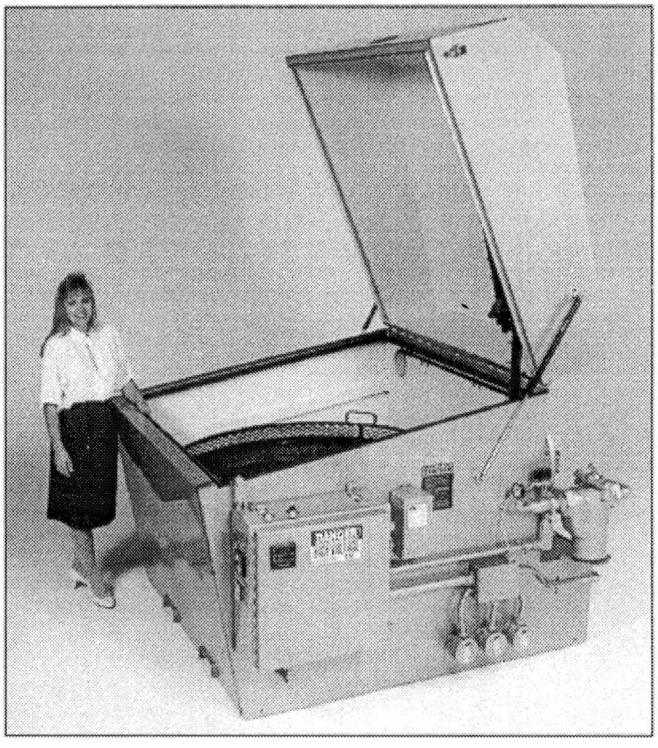

Figure 2.3.2 (a) Top-Load Batch Cabinet Spray Washer

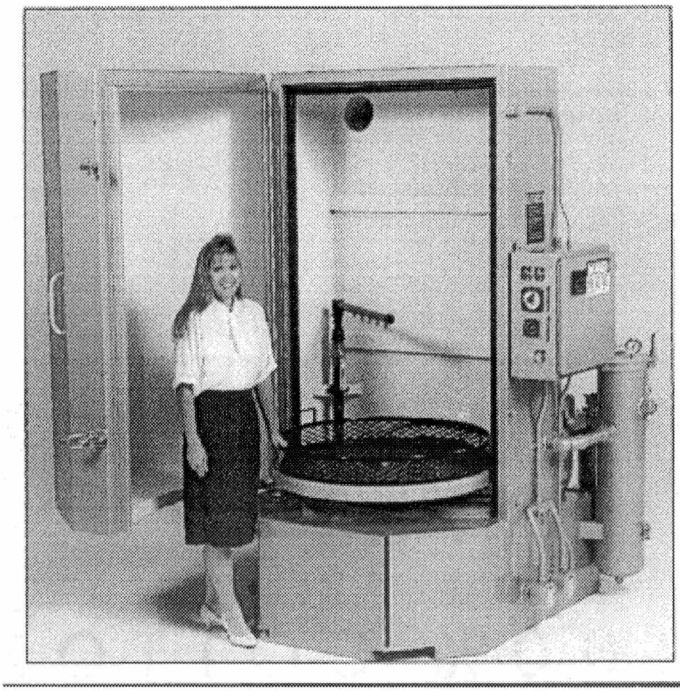

Figure 2.3.2 (b) Front-Load Batch Cabinet Spray Washer

parts. Furthermore, manufacturing production volume and throughput levels could suggest one cleaning configuration over another. In a spray system, factors which effect performance include the number of nozzles, spray pattern, distance from the parts surface, the time the part spends under the spray, and part orientation. Generally spray systems operate well under situations of gross soil contamination, loose soil contamination, large uncomplicated surface areas, i.e. no blind holes. Sprow suggests spray systems are ideal for light, sheet metal parts that would tend to float in an immersion system [31]. Parts not suitable for spray washing applications would include small parts of geometric peculiarity such as pen tips, and hypodermic needles.

Multistage cleaning is an equipment variation on the cabinet spray washer shown in Figure 2.3.2. In this configuration, the equipment may possess multiple reservoirs for the various stages of cleaning represented in Figure 2.1.1. This equipment configuration may take up less floor space than other equipment designed for linear parts flow through an equivalent cleaning process. A representative schematic of a multistage cleaning machine is shown in Figure 2.3.3. In this design, parts are loaded into a perforated basket which is then placed into rotating support frame located in a main chamber. The parts basket is then rotated while sprayed with cleaning solution pumped from a wash solution reservoir. Upon spraying, the main chamber begins to fill with the cleaning solution such that the parts become partially immersed in cleaning solution as they rotate; thus becoming subjected to both open air and immersed sprays. Once the wash cycle is completed, the volume of wash solution is pumped from the tank back into the wash reservoir. Subsequent stages of cleaning will mirror the wash stage. Multistage cleaning equipment may also offer a hot air dryer in the same chamber to complete the cycle. This is typical of the processing stages available with multistage equipment commonly referred to as power wash machines. Von Steeg has described one manufacturers'

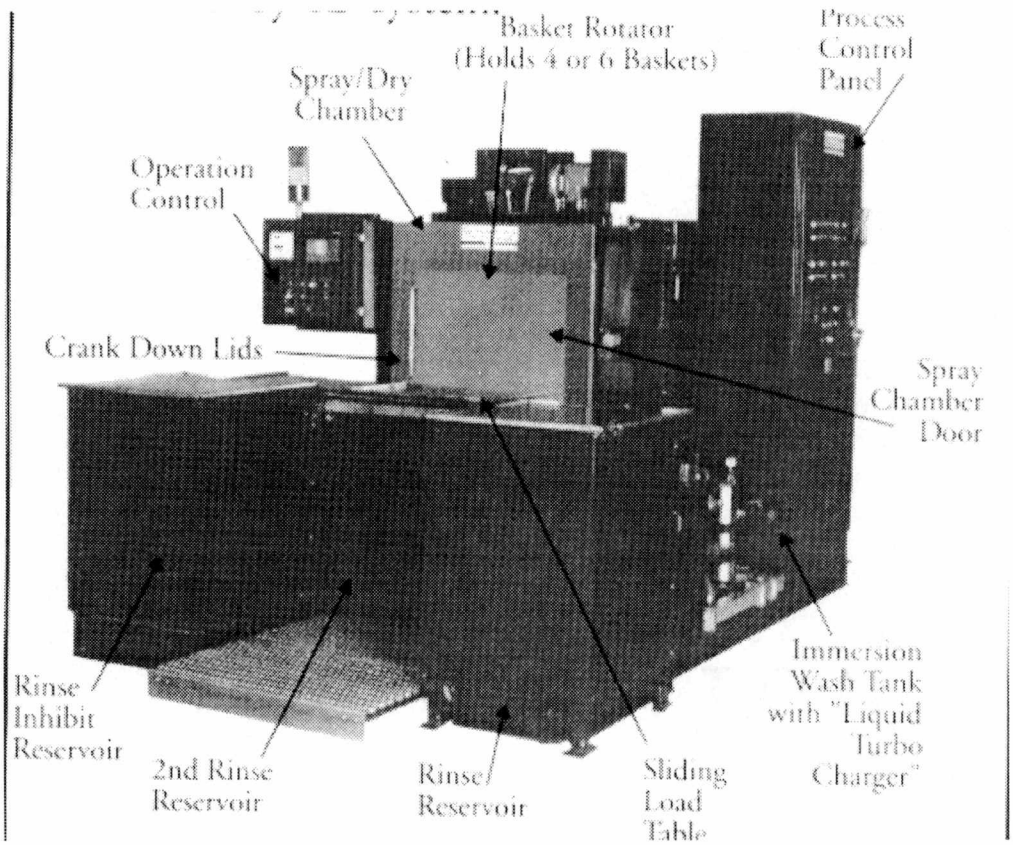

Figure 2.3.3 Multi-stage Equipment

multistage equipment in similar fashion [19]. Multistage equipment can vary from this scheme to others where the parts are contacted with each stage's solution. Some variations offered by vendors may include immersion of the parts into the wash solution reservoir for cleaning followed by their removal before subsequent rinse, treatment, and drying stages. These equipment schemes may be combined with ultrasonics, immersed sprays, and air knife blow-offs to reduce drag-out and facilitate drying.

Although vendors have used various materials of construction for many of these units, 300 series stainless steel is recommended for any wetted surface which will come into contact with corrosive media such as aqueous solutions and air [8].

Disadvantages of spray systems are said to include high initial cost, floor space and maintenance requirements, and energy consumption [31].

2.3.2 Immersion Equipment

All three alternative industrial cleaning processes can utilize immersion equipment. However it predominates in semi-aqueous and hydrocarbon cleaning. Immersion of the part into the wash agent allows it to wet the entire surface of the part and penetrate recessed areas and cavities. Hence the base unit for immersion equipment consists of a vessel or tank. Typical immersion tanks are shown in Figure 2.3.4.

Immersion cleaning processes as an alternative to vapor degreasing are popular because of their relative simplicity. Sprow has stated that agitation is the key to immersion cleaning processes [31]. Categorization of immersion processes are static immersion, immersion with mechanical agitation, and immersion with ultra or mega sonic transducers. Additionally equipment can be obtained which may combine the various methods of mechanical action. An immersion cleaning process utilizes individual tanks for each process stage represented in Figure 2.1.1 through Figure 2.1.4 with the exception of the drying stage. Tank sizing for immersion tanks was discussed in Section

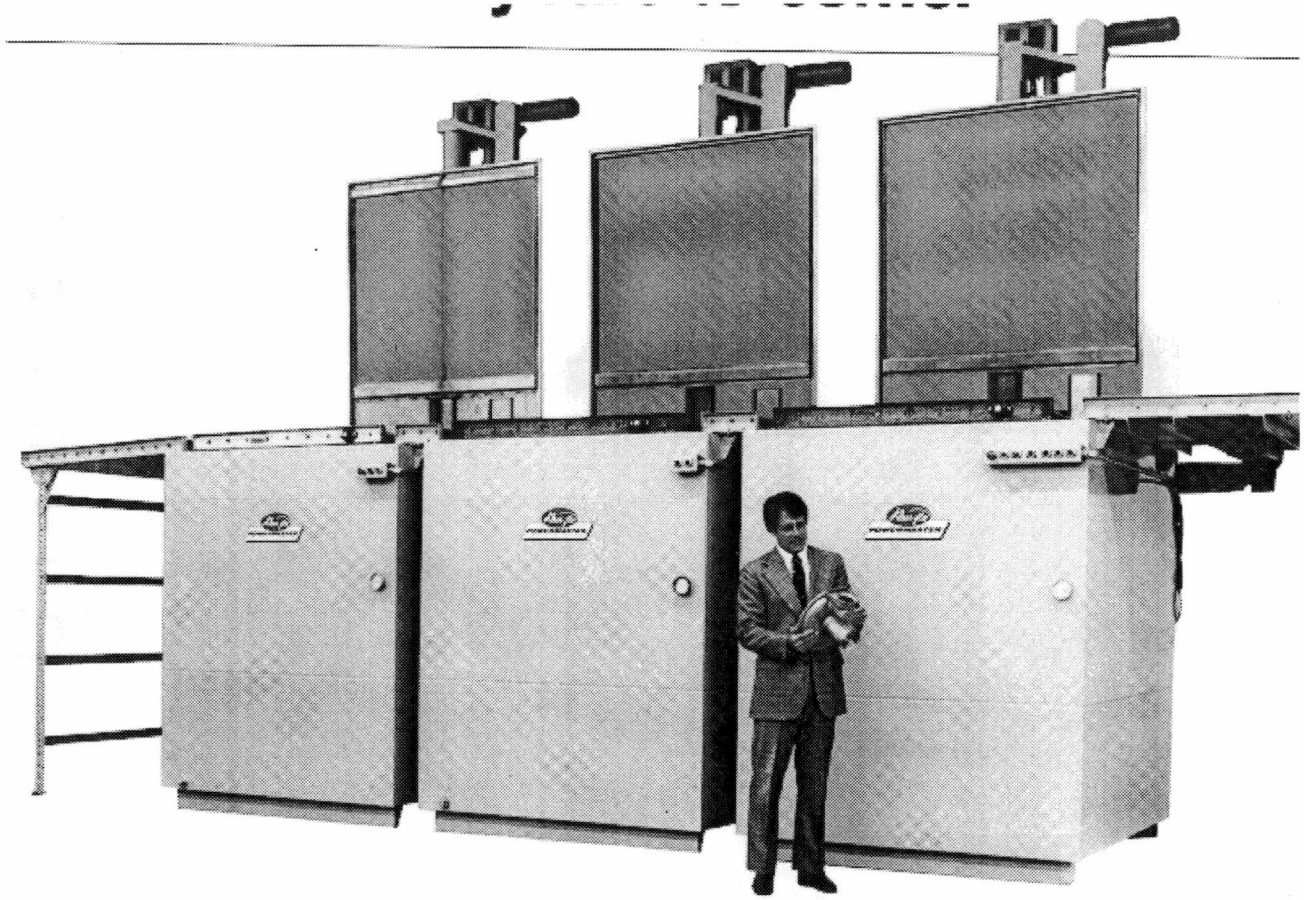

Figure 2.3.4 Immersion Tanks

2.1 of this thesis. In immersion processes, as a general rule of thumb 80 per cent of the cleaning is the result of chemical action on the soil by the wash agent. The remaining 20 per cent of the cleaning is the result of mechanical actions [43]. This rule is just opposite of that stated for spray systems. It is because of this dependence on chemical solvency that most immersion cleaning processes are hydrocarbon or semi-aqueous in nature. Semi-aqueous and hydrocarbon processes were discussed in Sections 2.2.2 and 2.2.3 of this thesis, respectively.

For both hydrocarbon and semi-aqueous cleaning, immersion equipment is similar. It consists of the tanks and associated piping and instrumentation. Forms of agitation include part rotation, part platform elevation, immersed jets, solution turbulation and ultrasonics. Not all solvents will be suitable with all forms of agitation. Care must be taken in solvent selection. Generally the form of agitation will be determined by the part geometry and configuration. If for instance the part is small and contains blind holes which will need to be flushed, then turbulation will be required. Flushing refers to turbulation of the cleaning medium, used to prevent resettling of the soil on the parts' surface. For very small parts or small blind holes then ultrasonics may be utilized. Ultrasonics is also effective in the removal of particles from a parts surface.

2.3.3 Immersion Tank Equipment Options

Skimmers: Oil skimmers of various configuration are used to remove oils from aqueous solutions and can often be found to be a standard feature on aqueous equipment. An oil skimmer consists of either a wide belt or disc half of which is immersed in the wash solution in a part of the reservoir tank referred to as a "quiet" tank. This may be an enclosed section of the reservoir tank which is protected from the agitation if the system is part of an immersion process or a totally separate tank. However the skimmer costs described in this thesis are a part of the immersion tank

itself. The belt or disc is slowly rotated into and out of the liquid upon which the coalescing oils adhere the disc's surface. This oil is then scraped from it's surface into channels which collect the oils. As oils coalesce, depending upon design; an oil skimmer can often remove 50-60 per cent of oil residues from wash solutions. The extent of success achieved with oil skimmers depends how quickly the oil and aqueous cleaner separate. Cleaner packages can be tailored to facilitate coalescence.

Particle filtration: A particle filtration system has become a standard feature of almost all industrial wash equipment. Particle retention sizes of 5-10 microns are usually encountered. Metal fines generated by metal machining operations fall within this filter range. Coalescing oils from wash solutions are also often removed. Continuous filtration is beneficial to a cleaning system as it serves to prolong wash solution life and prevents re-contamination of the part. A filter system consists of a liquid pump, cartridge filter, filter housing, pressure gauge, a flow control valve, and appropriate electrical/plumbing modules and hardware. The pressure gauge is used to indicate when the filter may need changing signified by an increase in the pressure drop across the gauge. The inlet to the pump connects to the wash tank drain port while the outlet of the filter makes connection to the fill port of the wash tank.

Ultrasonics: The use of ultrasonic energy has emerged as a prominent option for immersion configurations of industrial cleaning equipment. Sprow has stated that ultrasonics can provide the highest amount of agitation for an immersion cleaning process [31]. Ultrasonic equipment employs ultrasonics or sound waves generated at frequencies above 18 kilohertz (KHz) to provide cavitation within the bulk volume of the wash agent [18]. Cavitation is the combined formation and implosion of bubbles generated by the alternating rarefaction and compression areas of a sound wave as it moves through a liquid medium. Thus at any point in the bulk volume of the wash agent,

that lies in the path of the sound wave; both rarefaction and compression will occur. Rarefaction is an area of negative pressure which promotes the formation of unstable areas of partial vacuums or bubbles. These bubbles then immediately collapse as the sound wave moves; the result of compression from areas of positive pressure. Temperatures and pressures of 10,000 °F and 10,000 psi respectively, have been estimated at the point of implosion of these bubbles [52]. A more thorough treatment of the physical principles and governing theory of ultrasonics in liquids and their effects on matter are given by Nosov [53]. Although not specifically addressing industrial cleaning applications, Nosov documents the definitive role of cavitation in the breakdown of surface films, i.e. soil contamination layer on a part. It provides insight into the effect variables such as liquid viscosity and temperature can have on ultrasonic systems as well.

It is the powerful, imploding force generated by thousands of these bubbles that is taken advantage of in ultrasonic cleaning. These bubbles provide a mechanical "scrubbing" action to the surface of parts immersed in the ultrasonic environment. The size of the bubbles and hence the intensity of the "scrubbing" action is governed by the frequency of the sound waves. Frequencies most commonly encountered for industrial cleaning applications lie in a range from 20 to 50 KHz with 40 KHz generally regarded as optimum [18]. Industrial parts with blind holes or small surface irregularities benefit from the use of ultrasonics. However consideration must be given to the type of metal substrate and the time a part spends exposed. Ultrasonics can erode soft metals such as aluminum and brass. General Dynamics found ultrasonics to be useful in removing higher molecular weight soils and in cleaning complex part geometries [30]. Applicability and considerations of ultrasonics for immersion cleaning systems has been discussed by Fuchs [52,54].

The equipment required to generate ultrasonics is composed of transducers and power generators. The transducer consists of a metal encased vibrating element (piezoelectric disc). This is the actual mechanical means by which the ultrasonic waves are produced while the power generator provides the electrical signal and the means to vary the frequency modulation of the sound waves. The ultrasonics option considered in this thesis will consist of many individual transducer modules attached to the outer wall of the inner tank of the double hulled immersion tank. The power generator will be separate and have the capability for frequency modulation or sweep.

Mechanical agitation methods: A review of the literature reveals several means to introduce agitation between the part and the wash or rinse solutions. These include platform lifts, impeller turbulation, and several variations. In platform lift configuration, the parts are placed on a platform which is raised and lowered repeatedly in the wash or rinse solutions. Sprow has described one application of platform agitation in this manner: "a pneumatic arm lowers a pallet with a part basket into a tank and jogs it slowly up and down at rates adjustable up to several per minute" [31]. Spring has suggested that this form of agitation is frequently used with solvent cleaners [4]. For impeller turbulation systems, impellers are used to turbulate the wash/rinse solutions providing solution turnover. However, Spring has suggested that mechanical stirring is a relatively ineffective means of agitation [4].

Rotating basket mechanism: Often with immersion systems, a rotating basket is employed. This provides additional turbulation between the parts and the basket. In addition, in the case of very small parts, the tumbling action produced with a rotating basket mechanism can prevent the packed density of the mass of parts from interfering with the wash process. Situations such as this could be expected of parts such as pen

tips or similar parts. The tumbling of small parts can also facilitate drainage thus reducing the amounts of drag-out carried to the next processing stage.

Immersed jets: This option is also referred to as "spray-under-immersion". For immersion tank systems, it is the opposite application of open air spray. In this set-up, the jets are immersed below the level of the wash/rinse solutions. Impingment of the work package by the wash solution thus occurs below the air/solution interface. A typical system includes a liquid pump which circulates the wash solution from and back to the tank under pressure through a pipe network. The solution exits through nozzles or jets contained in a piping manifold which circumvents the parts being cleaned. Pump capacity must ensure sufficient flow of solution over the work package if this method is to provide adequate agitation.

Air Sparging System: This agitation option is also referred to as "air jet". In this agitation scheme, air is pumped under pressure through a perforated piping manifold located in the bottom of the immersion tank. This air rises through the liquid thus creating agitation between the part and wash solution. This form of agitation will stir the solution and any debris that may have settled on the bottom of the tank. It is for this reason that Spring has stated that this is not an effective option for the wash tank but may be for subsequent rinse tanks [4].

Vapor Extraction System: Solvent usage often requires adequate ventilation. This is especially true in the use of semi-aqueous and hydrocarbon immersion cleaning. The semi-aqueous solvent terpene and dibasic esters are especially known for their odor. Furthermore, particular solvents may react with a variety of soil contaminants creating a volatile vapors. A vapor extraction system will keep the vapor concentration above the solvent/air interface below the maximum allowable levels. A typical system consists of a vacuum pump and appropriate electrical\plumbing hardware. The inlet to the pump

connects to a vent port in the tank above the solvent/air interface. The outlet of the vacuum pump exits to an appropriate outside vent or to further treatment such as an activated carbon adsorption tower.

3.0 MODEL DEVELOPMENT

3.1 Process engineering cost models

Cost models can be found for most process equipment. Various sources exist for a great variety of process equipment such as those compiled by Walas [55], Vanatuk [56,57], and Popper [58]. Although the equipment may vary greatly, the method for development of a cost model is generally the same. Cost data supplied by an equipment vendor allows correlations to be developed which present the cost as a function of a primary design variable. Models of this sort provide cost estimates of budget or study-estimate quality, accurate within ± 30 per cent. The cost estimates they generate are free-on-board (FOB) and do not include auxiliary equipment, installation, or labor unless indicated. The FOB qualification signifies the retail cost of the equipment at the manufacturer's site and does not include shipping to it's final destination.

Two examples of typical equipment cost models encountered for the use in a process engineering analysis were those developed for plate-and-frame heat exchangers and shop fabricated storage tanks.

Vatavuk presented a cost model for plate-and-frame heat exchangers, 1995; represented by Equation (1) [56].

$$\text{Cost} = 231\ A^{.639} \qquad (1)$$

Here the cost of a plate-and-frame heat exchanger is presented as a function of the heat transfer area A in square feet; $50 \leq A \leq 9000$. The equation is plotted in Figure 3.1. Cost models are often presented in graphical form to visually illustrate the relationship

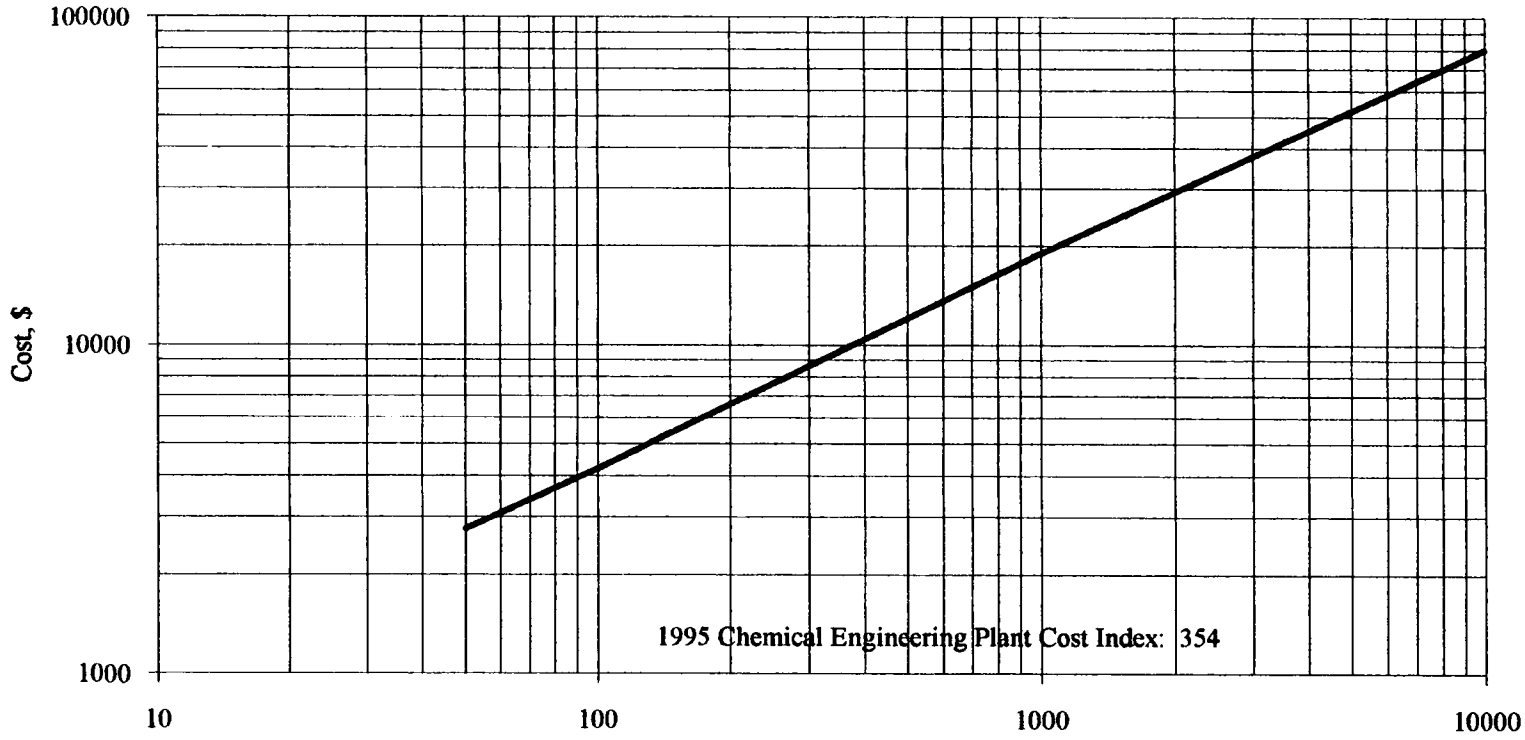

Figure 3.1 Plate-and-Frame Heat Exchangers (1995)

between the cost and the primary design variable. This serves to facilitate their use in obtaining quick equipment cost estimates.

Walas presented a cost model for shop fabricated storage tanks, 1985; represented by Equation (2) [59]. Their cost is represented as a function of volume (V), $1{,}300 \leq V \leq 21{,}000$ gallons and a material of construction factor, F_M.

$$\text{Cost} = F_M \exp[2.631 + 1.3673 (\ln V) - 0.06309 (\ln V)^2] \qquad (2)$$

A plot of Equation (2) is shown in Figure 3.2 for $F_M = 2.4$, stainless steel 304 construction.

It is very important to be aware of the date of the cost data used to develop the cost model. This date should be recorded along with the data. An appropriate index should be used to extrapolate the cost of equipment from the year in which the data was assembled to the current year. Several current cost estimate indices are available in Chemical Engineering Magazine [60]. Peters and Timmerhaus describe the function and use of cost indices [61].

3.2 Thesis Model Development

Vendor literature information was collected for the various configurations of industrial cleaning equipment that are commonly available. Two basic equipment configurations for cleaning were identified as capable of having their costs' modeled. These were immersion equipment suitable for all three alternative technologies and batch cabinet spray equipment suitable for aqueous and emulsion technologies.

In addition, eight primary options common to an immersion process were identified. These were ultrasonics, mechanical agitation, oil skimmers, particle filters,

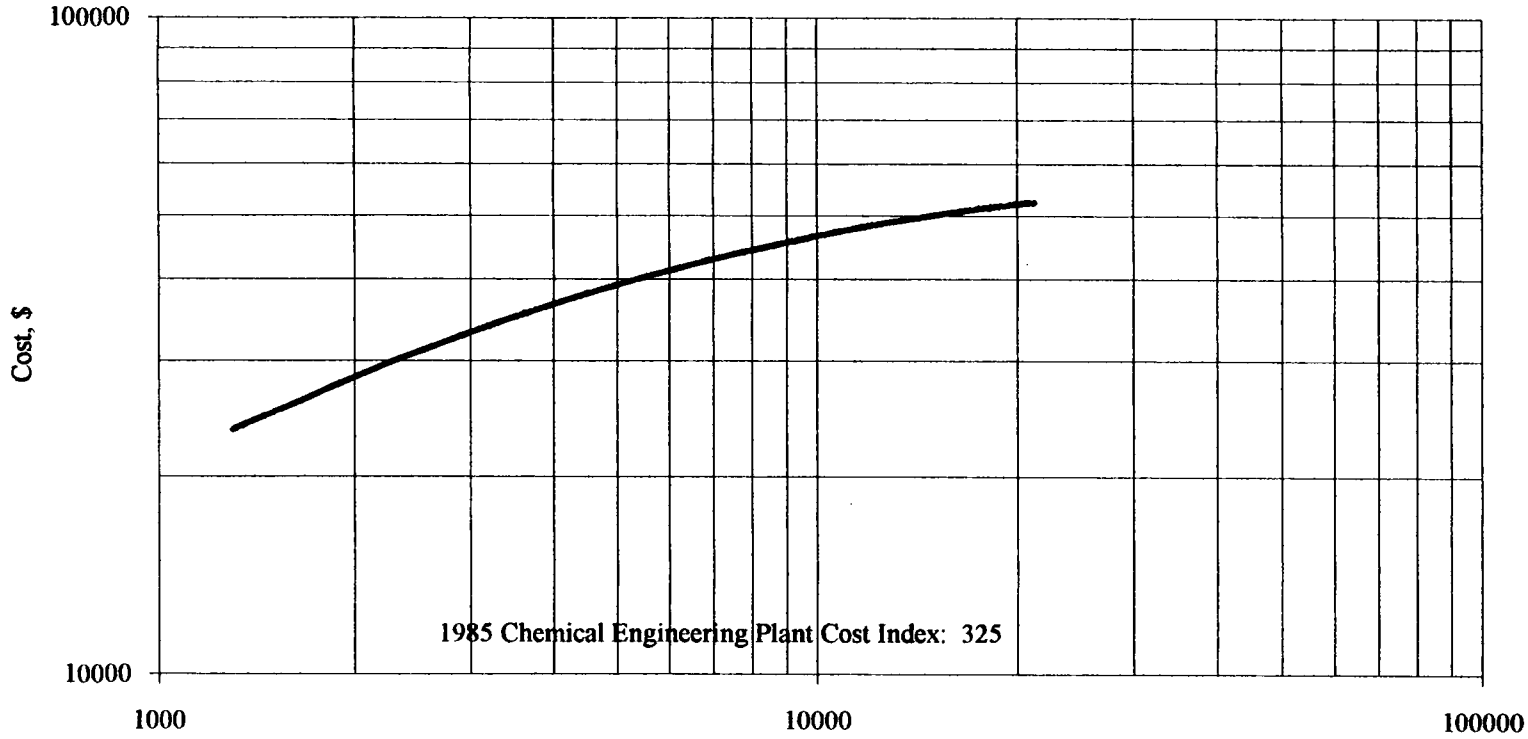

Figure 3.2 Shop Fabricated Storage Tanks (1985)

rotating basket, air spargers, immersed jets, and vapor extraction. The cost model for the equipment for a complete immersion industrial cleaning process was then proposed to be the summation of the cost of the base equipment and any desired options.

The primary piece of equipment for an immersion industrial cleaning process is the tank. Cost data for dual wall immersion tanks were collected from a variety of sources. These sources included vendor literature, personal communications, and equipment supply catalogs. This data is shown in Table 3.2.1. The data collected represented tank cost as a function of tank volume. Generally, the standard features of the immersion tank as described by the proceeding models are as follows. The tank is dual walled, constructed of either 300 series stainless steel or carbon steel. When combined materials are used in construction, 300 series stainless steel is used for the inner tank. Sandwiched in between tank walls is a layer of insulation provided to maintain heating efficiency and operator safety. Additionally, the base unit also includes an enclosed electric heat capability as well as drain and fill fittings and appropriate electrical control modules defined as on/off switch and heat control. Also included is a cover. Covers are necessary to minimize solution evaporation, prevent dust from the air from falling into the tank, and to reduce noise levels when in operation.

In the case of dual wall immersion tanks constructed of 300 series stainless steel, cost data was collected (1995). A linear regression analysis of this data was performed. The first order linear model obtained is shown as Equation (1a). A correlation coefficient of .995 was determined for this data. Equation (1a) is shown plotted in Figure 3.3 along with the ± 30 per cent quality levels expected of a study level estimate.

$$\text{Cost (\$)} = 34.5\ (V) + 2500 \qquad (1a)$$

Table 3.2.1 Immersion Tank Price Quotes (1995)

tank volume	materials of construction		
gallons	carbon steel	stainless steel	both c/ss*
10			$1,100
15	$890	$3,000	$1,800
22		$3,400	
40	$1,100		
60		$4,600	
90	$2,300		
100			$3,700
160			$5,300
180	$3,000		
200	$3,300		
250			$7,900
300	$3,800		$9,000
500			$13,000
525	$6,900		
530			$14,500

* carbon outer wall, stainless steel inner wall

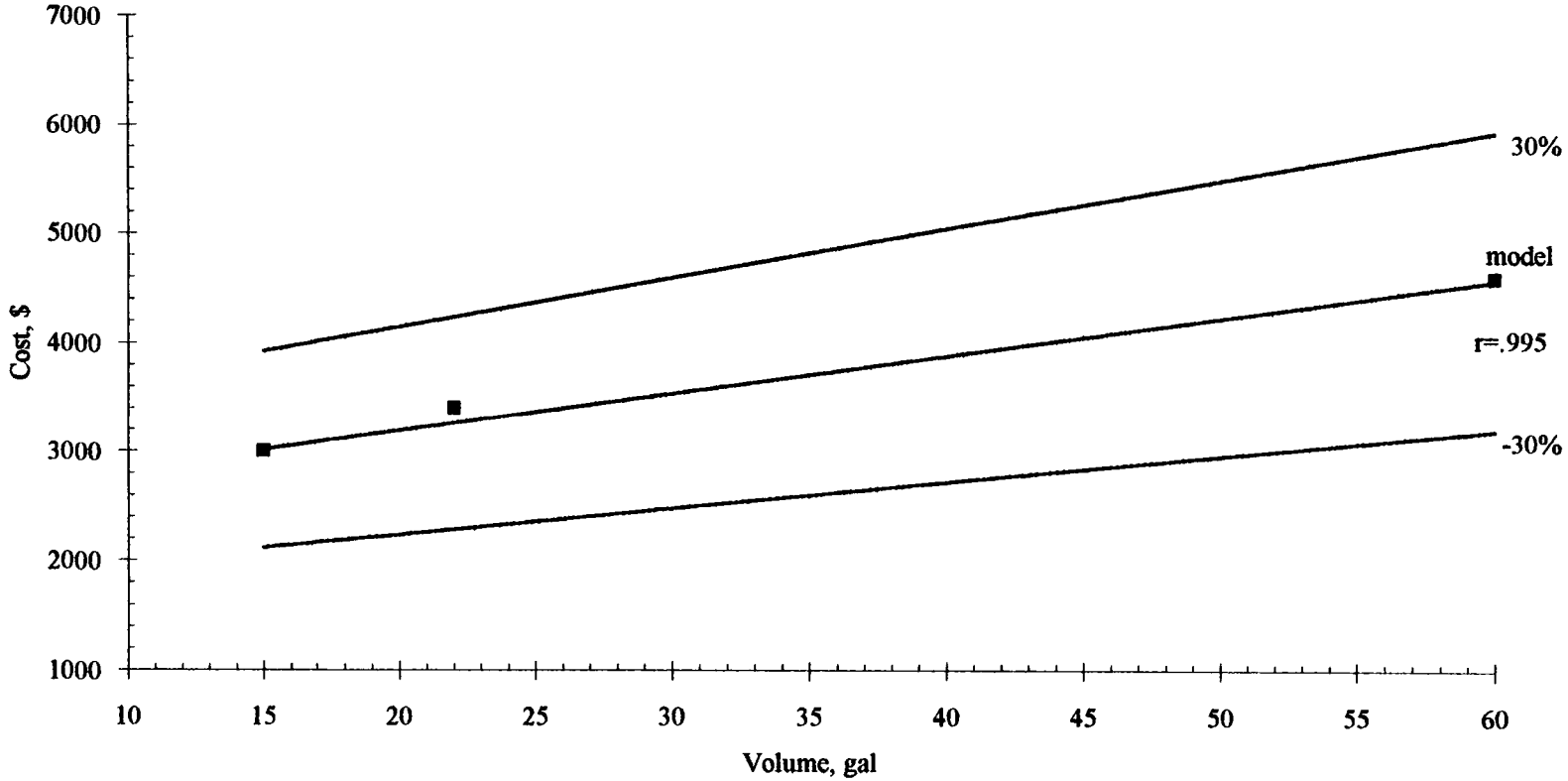

Figure 3.3 Stainless Steel Immersion Tanks (1995)

This model represents the cost of a dual wall stainless steel tank within the volume limit of $15 \leq V \leq 60$ gallons.

Cost data for dual wall tanks constructed of carbon based steel was collected (1995). A linear regression analysis of this data was performed. The first order linear model obtained is shown as Equation (1b). A correlation coefficient of .989 was determined for this data. Equation (1b) is shown plotted in Figure 3.4 along with the ± 30 per cent quality levels expected of a study level estimate.

$$\text{Cost (\$)} = 11\ (V) + 861 \qquad (1b)$$

This model represents the cost of a dual wall carbon steel tank within the volume limit of $15 \leq V \leq 525$ gallons.

Cost data for dual wall tanks constructed with a carbon based steel outer wall and an inner wall constructed of 300 series stainless steel was collected (1995). A linear regression analysis of this data was performed which showed a correlation coefficient of .997. The first order linear model obtained is shown as Equation (1c). This equation is plotted in Figure 3.5 with the ± 30 per cent quality levels expected of a study level estimate.

$$\text{Cost (\$)} = 25\ (V) + 1310 \qquad (1c)$$

This model represents the cost of a dual wall tank within the volume limit of $10 \leq V \leq 530$ gallons.

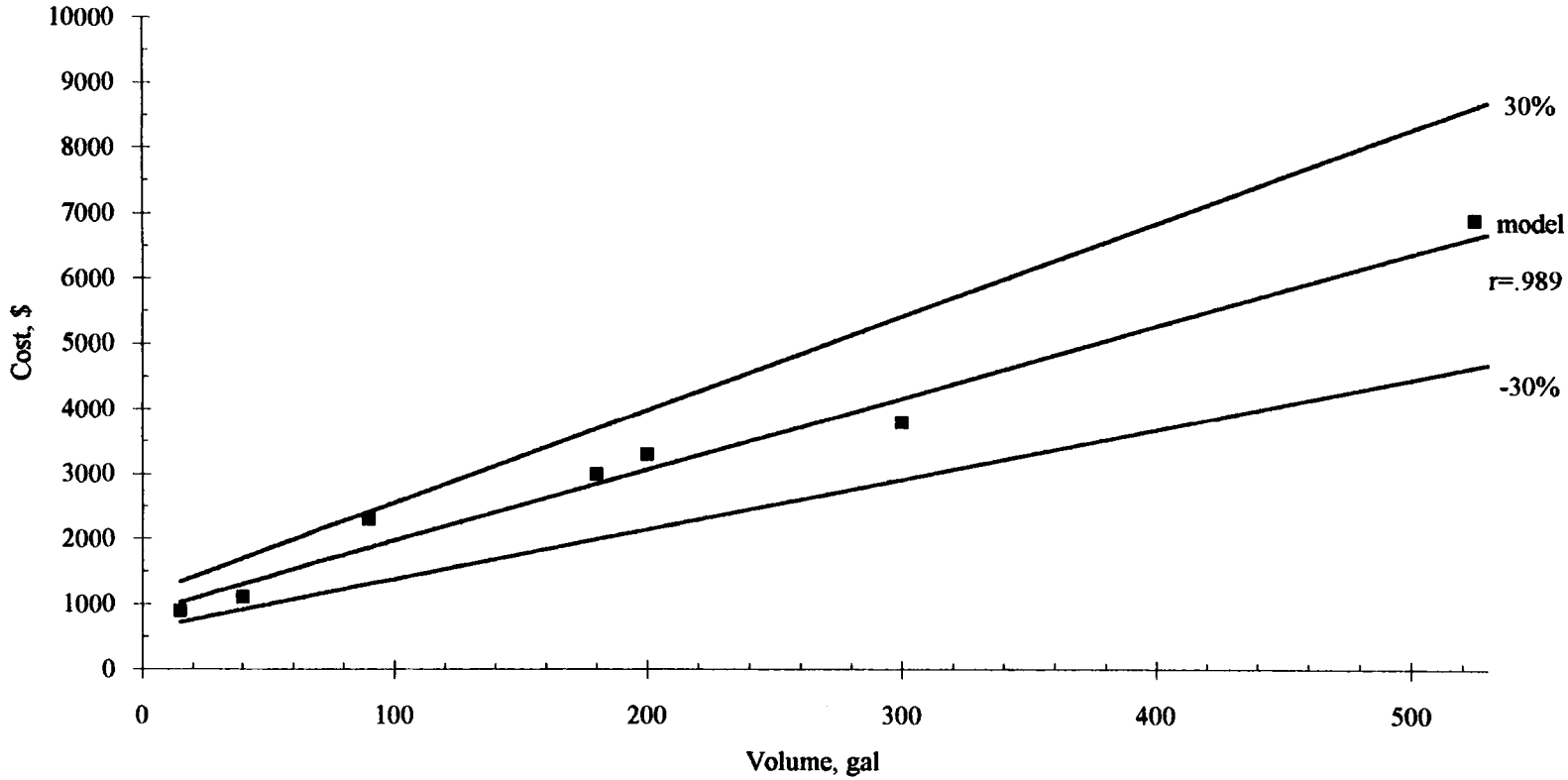

Figure 3.4 Carbon Steel Immersion Tanks (1995)

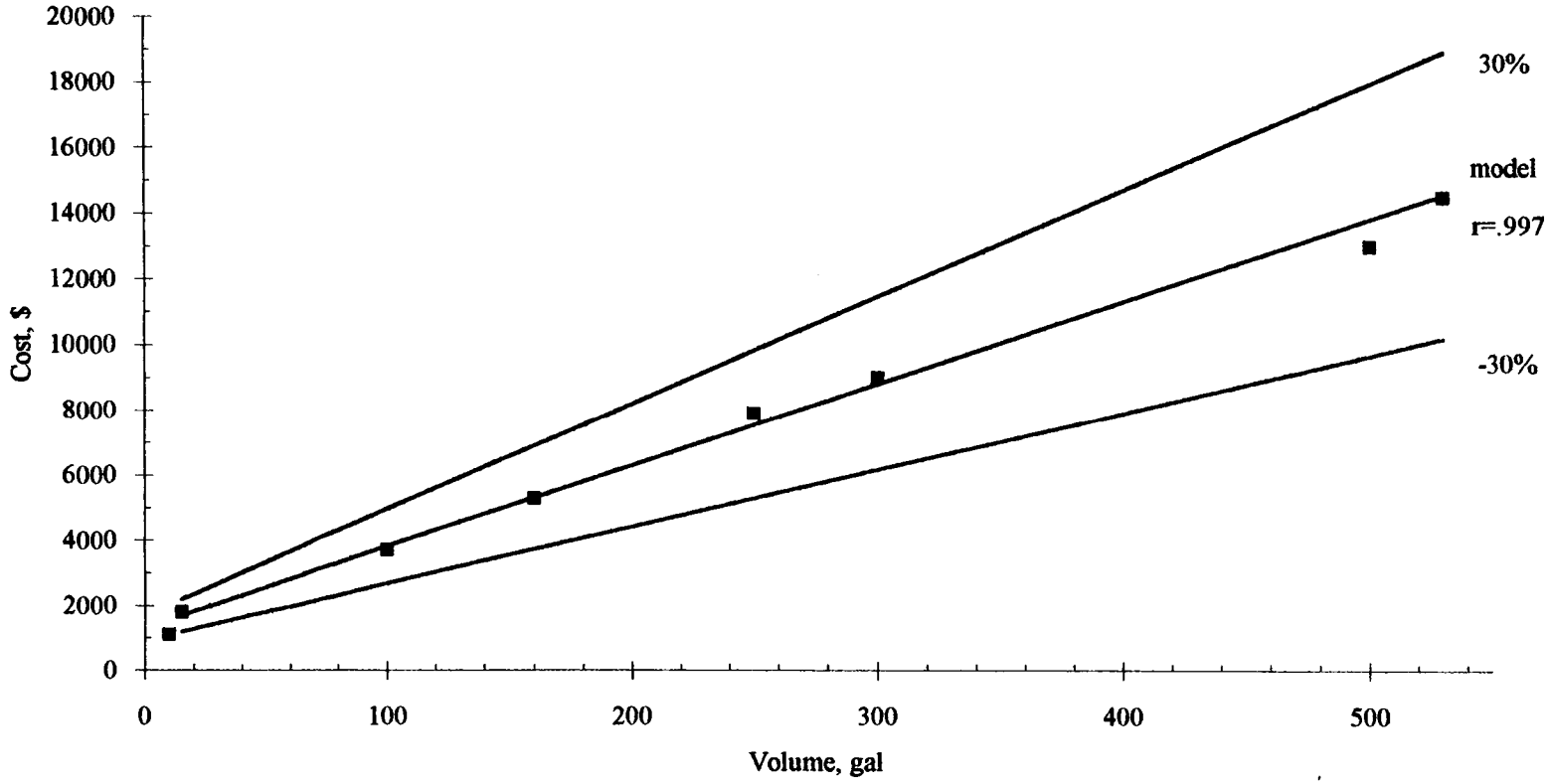

Figure 3.5 Carbon/Stainless Steel Immersion Tanks (1995)

A different approach was taken for the task of modeling the additional cost incurred by the inclusion of any of the eight primary options to an immersion process tank.

For the inclusion of ultrasonics, a linear relationship was suggested to exist between cost and tank size over the range of tank volumes represented by Equations (1a), (1b), and (1c) [8]. The proposed model for the additional cost of ultrasonics to a basic immersion tank is shown as Equation (1d) (1995).

$$\text{Cost}_{\text{ultrasonics}}\ (\$) = 97\ (V) \qquad (1d)$$

This model describes the cost of permanent ultrasonic transducers to be placed between the dual walls of an immersion tank during manufacturing. It also captures the cost of the power generator and frequency regulator necessary to complete the ultrasonic option.

The remaining seven process options identified and described in Section 2.3.3 represent potential additional costs to a basic immersion tank. It is suggested that for various ranges of immersion tank sizes, the cost of each option can be assumed constant. This simplified the approach making it a more convenient corollary to SAGE. Table 3.2.2 lists these options and suggested cost increments for determining the total cost of the cleaning equipment. These cost elements and ranges of applicability were determined from a review which included vendor literature, industrial supply catalogs, and personal communications (1995) [8].

The projected total cost for the equipment for an immersion industrial cleaning process is given by Equation (1f) with the basic immersion tank cost described by

Table 3.2.2 Immersion Tank Optional Equipment Cost Increments (1995)

<table>
<tr><th rowspan="2">Tank Volume, gallons</th><th colspan="7">Optional Equipment Costs</th></tr>
<tr><th>Oil Skimmers, $</th><th>Particle Filters, $</th><th>Rotating Basket, $</th><th>Mechanical Agitation, $</th><th>Air Sparger, $</th><th>Immersed Jets, $</th><th>Vapor Extraction, $</th></tr>
<tr><td>15</td><td rowspan="4">350</td><td rowspan="3">2600</td><td rowspan="2">600</td><td rowspan="2">800</td><td rowspan="3">450</td><td rowspan="2">500</td><td rowspan="4">1100</td></tr>
<tr><td>20</td></tr>
<tr><td>30</td><td rowspan="3">1000</td><td rowspan="3">1600</td><td rowspan="3">900</td></tr>
<tr><td>40</td></tr>
<tr><td>50</td><td rowspan="5">3600</td><td rowspan="4">800</td></tr>
<tr><td>60</td><td rowspan="4">500</td></tr>
<tr><td>70</td><td rowspan="2">1500</td><td rowspan="2">3000</td><td rowspan="3">1600</td><td rowspan="3">1800</td></tr>
<tr><td>80</td></tr>
<tr><td>90</td><td rowspan="2">3000</td><td rowspan="2">1400</td></tr>
<tr><td>100</td><td>4000</td></tr>
<tr><td>200</td><td rowspan="2">600</td><td>4500</td><td>6000</td><td>5000</td><td>1700</td><td rowspan="2">2400</td><td rowspan="5">2500</td></tr>
<tr><td>300</td><td>5500</td><td>9000</td><td>7000</td><td>2400</td></tr>
<tr><td>400</td><td rowspan="3">750</td><td rowspan="3">6300</td><td rowspan="3">N. A.</td><td>9000</td><td>3200</td><td>3000</td></tr>
<tr><td>500</td><td>11500</td><td rowspan="2">3800</td><td rowspan="2">3500</td></tr>
<tr><td>550</td><td>13000</td></tr>
</table>

Equations (1a), (1b), and (1c) and the cost options described in the models of Equations (1d) and/or the option cost elements of Table 3.2.2.

$$Cost_{total} = C_{base} + C_{option1} + C_{option2} + \ldots\ldots\ldots \quad (1f)$$

The installation cost of an immersion system was investigated by reviewing the installation costs of other process equipment [55,58,61,62]. These costs are customarily represented as a percentage of the total purchased equipment cost. The review revealed; depending upon the equipment, that estimates ranging from 20 to 90 per cent of purchased equipment cost are common. However it was suggested that the lower end of this range may be most suitable for predicting the installation costs of immersion equipment [8]. Therefore the cost of installation for a complete immersion equipment system is proposed to represent 20 per cent of the total purchased equipment cost represented by Equation (1f) using the cost model for the immersion tank constructed of dual materials, carbon and stainless steel shown as Equation (1c). The cost of installation for an immersion system is shown as Equation (1g).

$$Cost_{installation} = 0.20 \, (Cost_{total}) \quad (1g)$$

Therefore the total installed equipment cost for an immersion system is proposed to be predicted by Equation (1h).

$$Cost_{installed\ equipment\ total} = Cost_{installation} + Cost_{total} \quad (1h)$$

Cost data was collected for batch cabinet spray wash equipment (1995). This data is shown in Table 3.2.3. A linear regression analysis of this data was performed. The first order linear model obtained is shown as Equation (2). The results of this regression are plotted in Figure 3.6 along with the ±30 per cent error intervals required of an estimate of study level quality. The correlation coefficient calculated for this regression analysis was .980 as shown in Figure 3.6.

$$Cost_{equipment}\ (\$) = 34\ (\ V_t\ ) + 5023 \qquad (2)$$

This model predicts the cost of batch cabinet spray wash equipment of either top-load or front-load configuration as a function of total equipment volume. Total equipment volume is the summation of both the reservoir tank volume, V_r, and the associated spray chamber volume, V_c. For Top-load equipment configurations, this model is based upon volume limits of $18<V_r<320$ gallons for the reservoir volume and $30<V_c<928$ gallons for the associated spray chamber volume. Therefore the total equipment volume limit for top-load configurations is $48<V_t<1193$ gallons. For front-load equipment configurations, the reservoir and spray chamber volume limits are $65<V_r<200$ gallons and $83<V_c<513$ gallons, respectively. The total equipment volume limit for front-load configurations is therefore $148<V_t<713$ gallons.

As with immersion equipment, a review of literature was done to find a basis on which to estimate installation costs for batch cabinet spray wash equipment. The review revealed no comparable standard equipment from which to estimate these installation costs. However this equipment is generally regarded as requiring minimal attention for installation and therefore minimal cost compared to other process equipment [8]. The

Table 3.2.3 Batch Cabinet Spray Wash Equipment Price Quotes* (1995)

type**	reservoir volume (gal)	Spray Chamber			total volume(gal)	pump characteristics			quote
		height, in	diameter, in	volume(gal)		hp	pressure(psi)	flow(gpm)	
TL	40	18	24	38	78	3	45	60	**$5,500**
TL	34	30	29	83	117	2	45	35	**$13,000**
TL	150	36	50	309	459	10	55	190	**$20,000**
TL	140	36	60	445	585	10	60	190	**$25,000**
FL	65	36	27	90	155	5	50	130	**$9,700**
FL	85	48	35	204	289	5	50	130	**$14,000**
FL	105	54	42	324	429	10	60	190	**$18,500**
FL	180	60	47	454	634	15	60	270	**$28,795**
TL	320	33	72	586	906	10	60	200	**$35,495**

* represents data from 4 equipment vendors

** TL (Top Loading), FL (Front Loading)

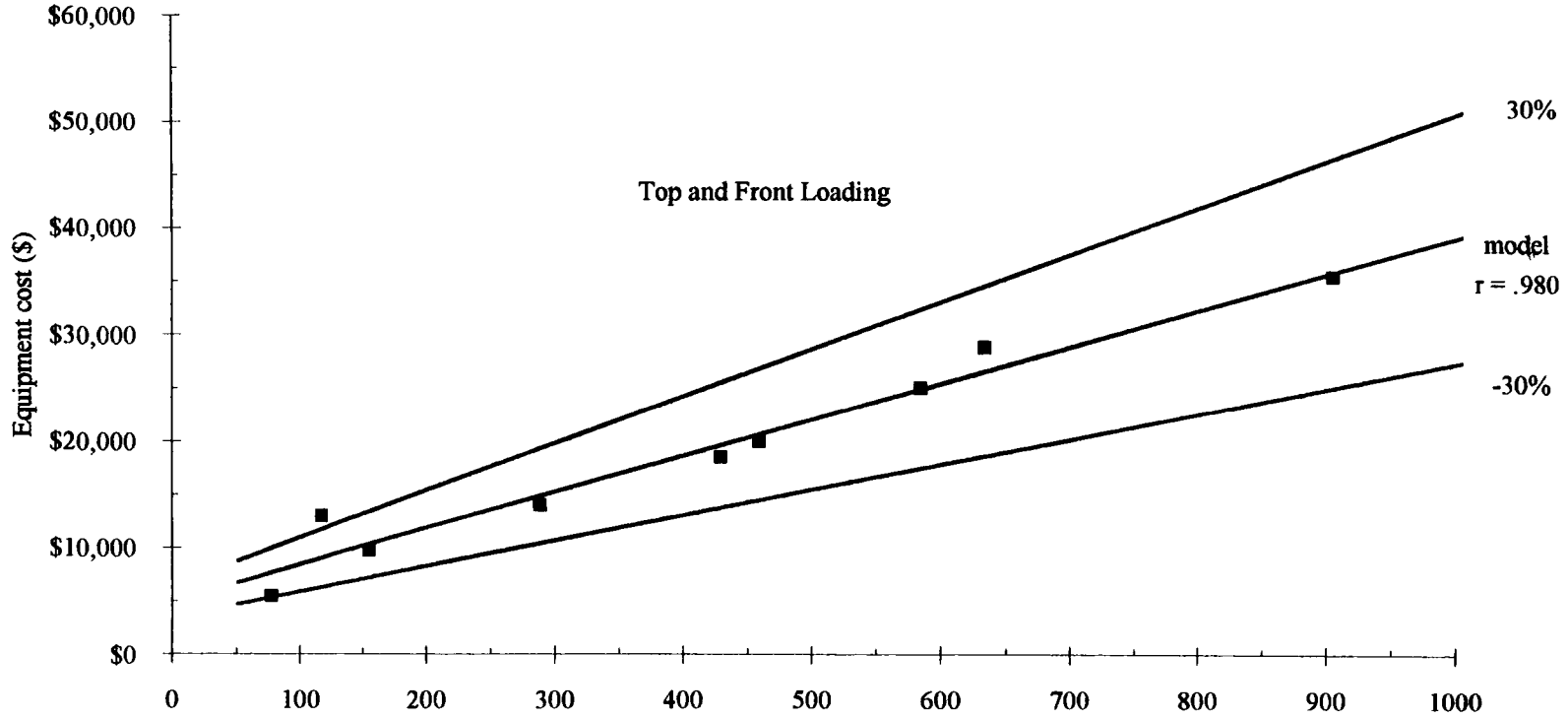

Figure 3.6 Batch Cabinet Spray Wash Equipment (1995)

installation costs are proposed in this thesis to therefore represent 8-12 per cent of the purchased equipment cost. This is shown as Equation (2a).

$$Cost_{installation}\ (\$) = 0.10(Cost_{equipment}) \qquad (2a)$$

Total cost for installed batch cabinet spray wash equipment is thus proposed to be represented by Equation (2b).

$$Cost_{installed\ equipment\ total}\ (\$) = 1.10\ (Cost_{equipment}) \qquad (2b)$$

4.0 MODEL DISCUSSION

The models proposed to estimate the costs of stainless steel and carbon steel immersion tanks represented by Equations (1a) and (1b) respectively, display a general relationship to each other. Stainless steel immersion tanks as described in this thesis appear to be 3 times the cost of carbon steel tanks. Although the upper limit of the model presented for stainless steel constructed tanks is 60 gallons, this suggests that it may be possible to predict the costs of larger stainless steel immersion tanks using the model for carbon steel tanks and a materials of construction factor of 3.0. Not as clear a relationship is seen to exist between the other materials of construction.

The costs elements shown in Table 3.2.2 for each immersion tank option are those additional costs incurred by their inclusion into the basic immersion tank and include all ancillary equipment to make the option complete. The expected cost of addition of each option mentioned in Section 2.3.3 of this thesis to both 45 and 280 gallon tanks is highlighted in Table 4.1. When using Table 4.1, the tank volume increments represent the upper limit of the volume interval. As Table 4.1 illustrates, the cost of addition of oil skimmers, particle filtration, rotating basket, mechanical agitation, air sparging, immersed jets, and vapor extraction for a 45 gallon tank are projected to be $350, $3600, $1000, $1600, $800, $900, and $1100 respectively. Similarly the costs of these options for a 280 gallon immersion tank are $600, $5500, $9000, $7000, $2400, $2400, $2500 respectively.

The most notable observation of the models presented in this thesis is the additional cost of ultrasonics to a basic immersion cleaning tank. The cost model presented for the ultrasonics option, Equation (1d); projects the cost of ultrasonics as 8.8 times the cost of the basic immersion tank constructed of carbon steel and 3.9 and 2.8

Table 4.1 45 and 280 Gallon Immersion Tank Cost Increments (1995)

Tank Volume, gallons	Optional Equipment Costs						
	Oil Skimmers, $	Particle Filters, $	Rotating Basket, $	Mechanical Agitation, $	Air Sparger, $	Immersed Jets, $	Vapor Extraction, $
15	350	2600	600	800	450	500	1100
20							
30							
40			1000	1600		900	
50		3600			800		
60	500		1500	3000		1600	1800
70							
80							
90			3000	4000	1400		
100							
200	600	4500	6000	5000	1700	2400	2500
300		5500	9000	7000	2400		
400	750	6300	N. A.	9000	3200	3000	
500				11500	3800	3500	
550				13000			

times the cost of tanks of combined materials and stainless steel respectively. As these models clearly show, the ultrasonics option can significantly increase the cost of immersion equipment. Therefore, the selection of ultrasonic equipment is not one that should be taken lightly and instead should be application specific. The mechanical forms of agitation such as impeller agitation or platform lift are also significant additions to the cost of immersion equipment; however their cost is only roughly 25 per cent of the cost of the ultrasonic option.

The rotating basket mechanism requires some mention concerning its' suitability for use. This option is often required for small parts which can withstand tumbling and may be considered a form of mechanical agitation. Often, a rotating basket mechanism will be part of an overhead hoist or parts handling mechanism separate from the actual tank itself; however it was included separately because it is available as a standard feature on some commercially available equipment. This feature is limited to size however, and is only applicable to tank sizes of $\leq$300 gallons. Larger tanks require an overhead hoist or additional parts handling capabilities as stated.

The immersion tank models introduced in Section 3.2 were used to estimate the costs of three commercially available immersion tanks. How these estimates compared with the actual quotes can be seen in Table 4.2. In comparison #1, the immersion tank was constructed of both stainless and carbon steel. In addition, it had 3 primary options: oil skimmer, rotating basket mechanism, and mechanical agitation. The model predicted the cost of the immersion tank within 12 per cent of the actual quote. In comparisons 2 and 3 both immersion tanks were constructed of carbon steel and had mechanical agitation as their only option. The model predicted the costs of the tanks within 10 and 1 per cent for comparisons 2 and 3, respectively. For the three pieces of equipment compared in Table 4.2, the models suggested in this thesis provided estimates within the

Table 4.2 Model versus Quote Comparisons

Comparison #1

Commercial Equipment Bowden RB-300 Single stage immersion tank (300 gallons) Constructed of stainless steel and carbon steel Options: oil skimmer, rotating basket, mechanical agitation		Quote	$28,990
Model Tank Options (Table 2.4.2)	Cost = 25*(300 gal) + 1310 = $8,810 Oil skimmer = $600 Rotating basket = $9,000 Mechanical Agitation = $7,000	Model Estimate	$25,410
		Difference	12%

Comparison #2

Commercial Equipment Kleer-flo PW500AME Single stage immersion tank (200 gallons) Constructed of carbon steel Options: mechanical agitation		Quote	$8,995
Model Tank Options (Table 2.4.2)	Cost = 11*(200 gal) + 861 = $3,061 Mechanical Agitation = $5,000	Model Estimate	$8,061
		Difference	10%

Comparison #3

Commercial Equipment Kleer-flo PW2000AME Single stage immersion tank (525 gallons) constructed of carbon steel Options: mechanical agitation		Quote	$19,900
Model Tank Options (Table 2.4.2)	Cost = 11 (525 gal) +861 = $6,636 Mechanical Agitation = $13,000	Model Estimate	$19,636
		Difference	1%

±30 per cent accuracy levels required of study estimate. This suggests they may be useful for estimating the costs of industrial cleaning immersion tanks for certain applications. However, other option variations for immersion tanks should be determined and modeled and then compared to vendor quotes.

Order-of-magnitude cost estimates listed in Table 2.1.1 are often made by estimating equipment cost by scaling. Estimates of this nature are subject to a quality of ±40 per cent. Timmerhaus describes this scaling technique in the following manner "if the cost of a given unit at one capacity is known, the cost of a similar unit with X times the capacity of the first is approximately $(X)^n$ times the cost of the initial unit." [55]. This is illustrated by Equation (1).

$$\text{Cost of equip. a} = \text{cost of equip. b} \left(\text{capac. equip. a} / \text{capac. equip. b}\right)^n \qquad (1)$$

The exponent n of Equation (1) is determined from the slope of a log-log plot of capacity versus cost which should be a straight line for this technique to be applied. Typical exponents for different process equipment are shown in Table 4.3 [55]. A great simplification of this cost estimating technique is called the "six-tenths factor rule" [1]. In this case, the value of the exponent n is 0.60. Historically, 0.60 represents the average for the exponents which have been calculated for the great variety of process equipment traditionally found in the chemical process industry. However, this rule should only be used in the absence of other information.

Log-log plots of the data collected for immersion tanks as shown in Table 3.2.1 and batch cabinet spray wash equipment as shown in Table 3.2.3 were developed. These are shown as Figures 4.1, 4.2, 4.3, and 4.4. The exponents determined from these plots are shown in Table 4.4.

Table 4.3 Typical Exponents for Equipment Cost versus Capacity

Equipment	Size range	Exponent
Blower, centrifugal	1000-10,000 ft3/min	0.59
Crystallizer, vacuum batch, carbon steel	500-7,000 ft3	0.67
Dryer, drum, single vacuum	10-100 ft2	0.76
Dryer, drum, single, atmospheric	10-100 ft2	0.4
Fan, centrifugal	1000-10,000 ft3/min	0.44
Kettle, cast iron, jacketed	250-800 gal	0.27
Kettle, glass-lined, jacketed	200-800 gal	0.31
Reactor, stainless steel, 300 psi	100-1000 gal	0.54
Separator, centrifugal, carbon steel	50-250 ft3	0.49
Tank, flat head, carbon steel	100-10,000 gal	0.57
Tank, carbon steel, glass lined	100-1000 gal	0.49
Tray, sieve, carbon steel	3-10 ft diameter	0.86

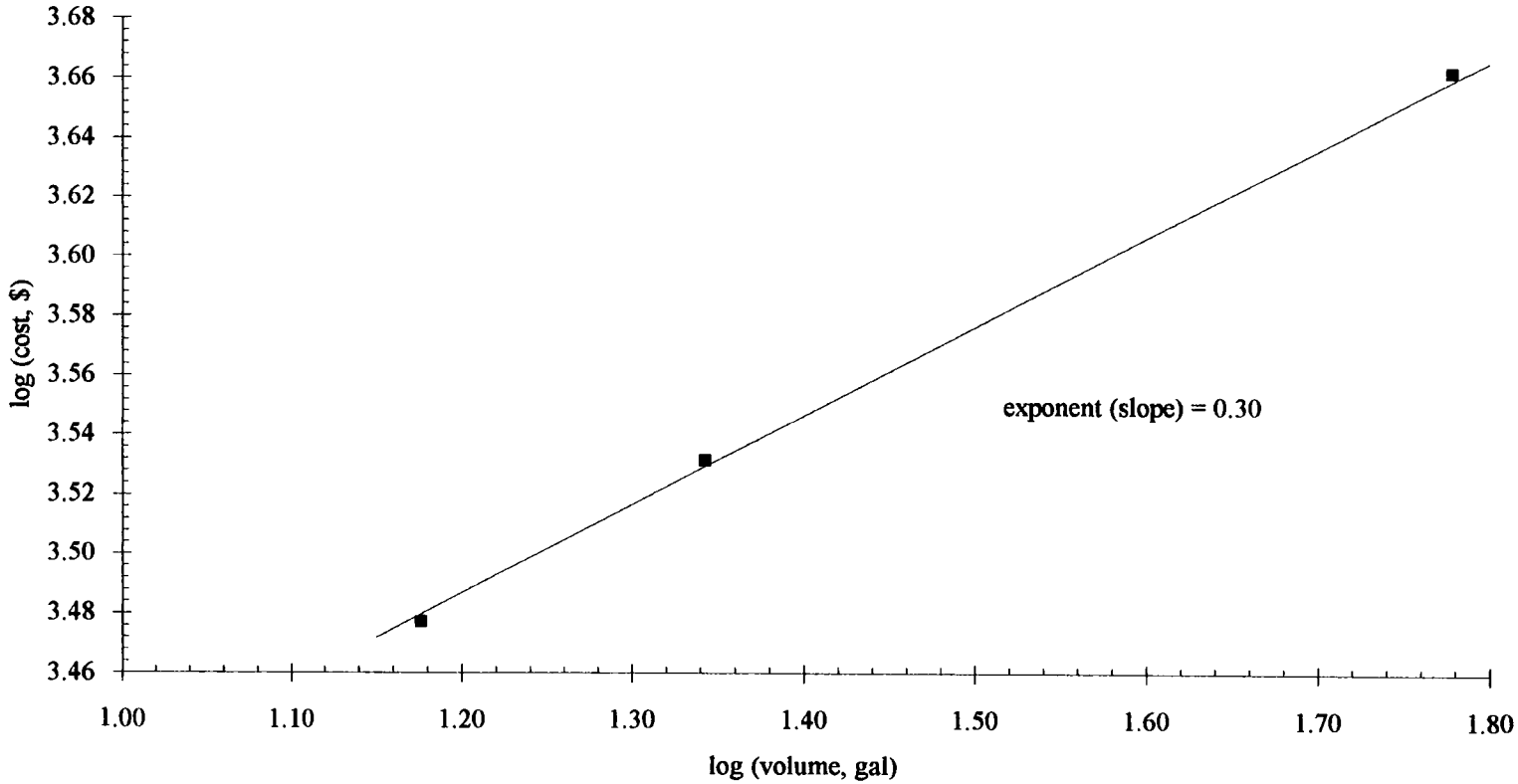

Figure 4.1 Log-Log Plot of Stainless Steel Immersion Tanks (1995)

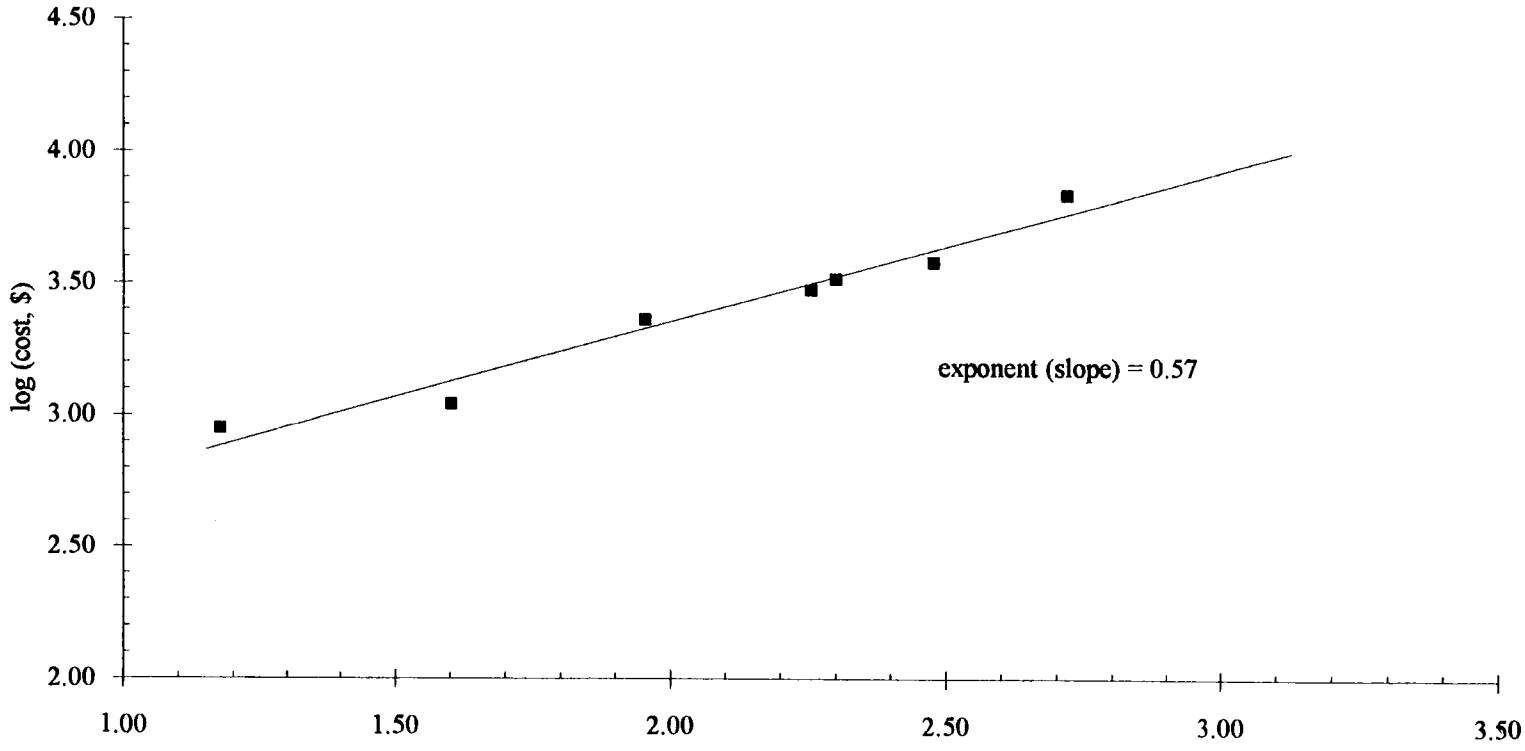

Figure 4.2 Log-Log Plot of Carbon Steel Immersion Tanks (1995)

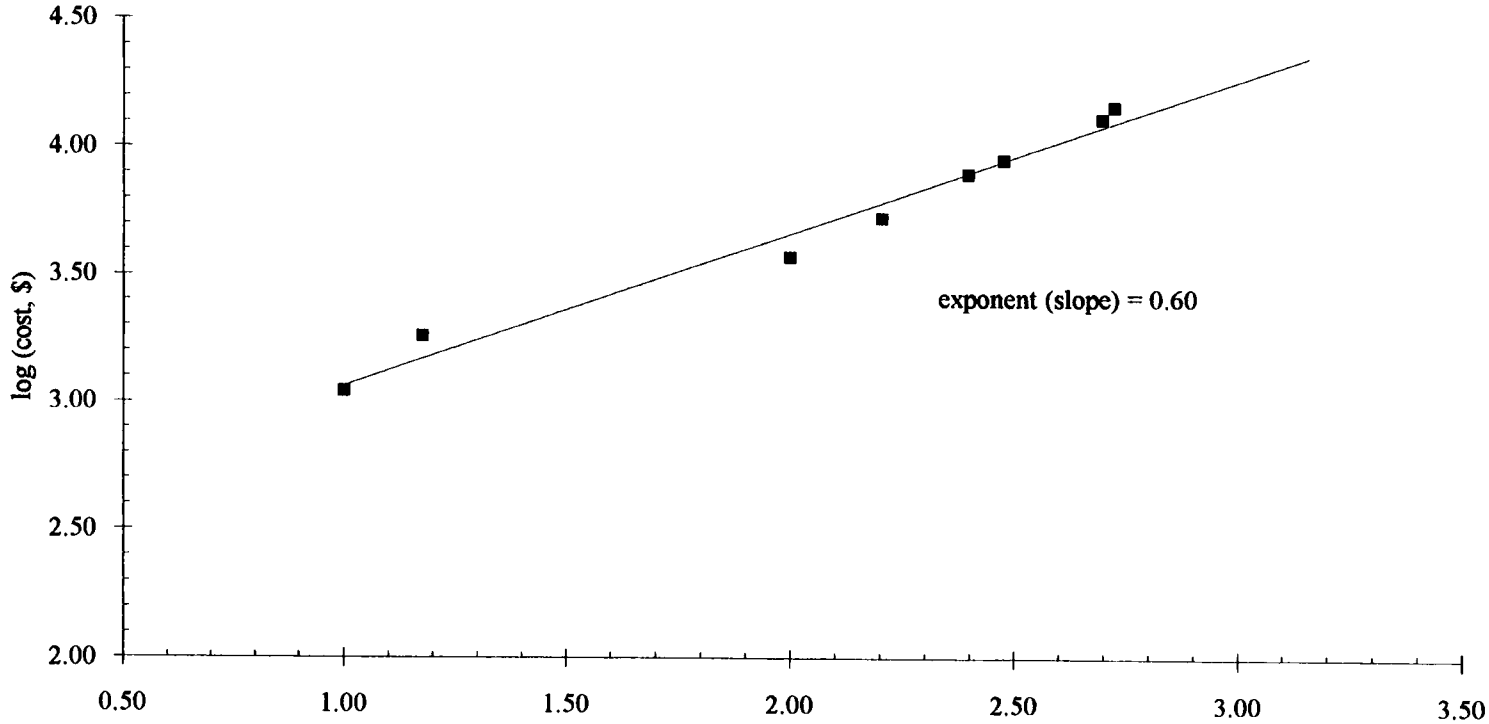

Figure 4.3 Log-Log Plot of Carbon/Stainless Steel Immersion Tanks (1995)

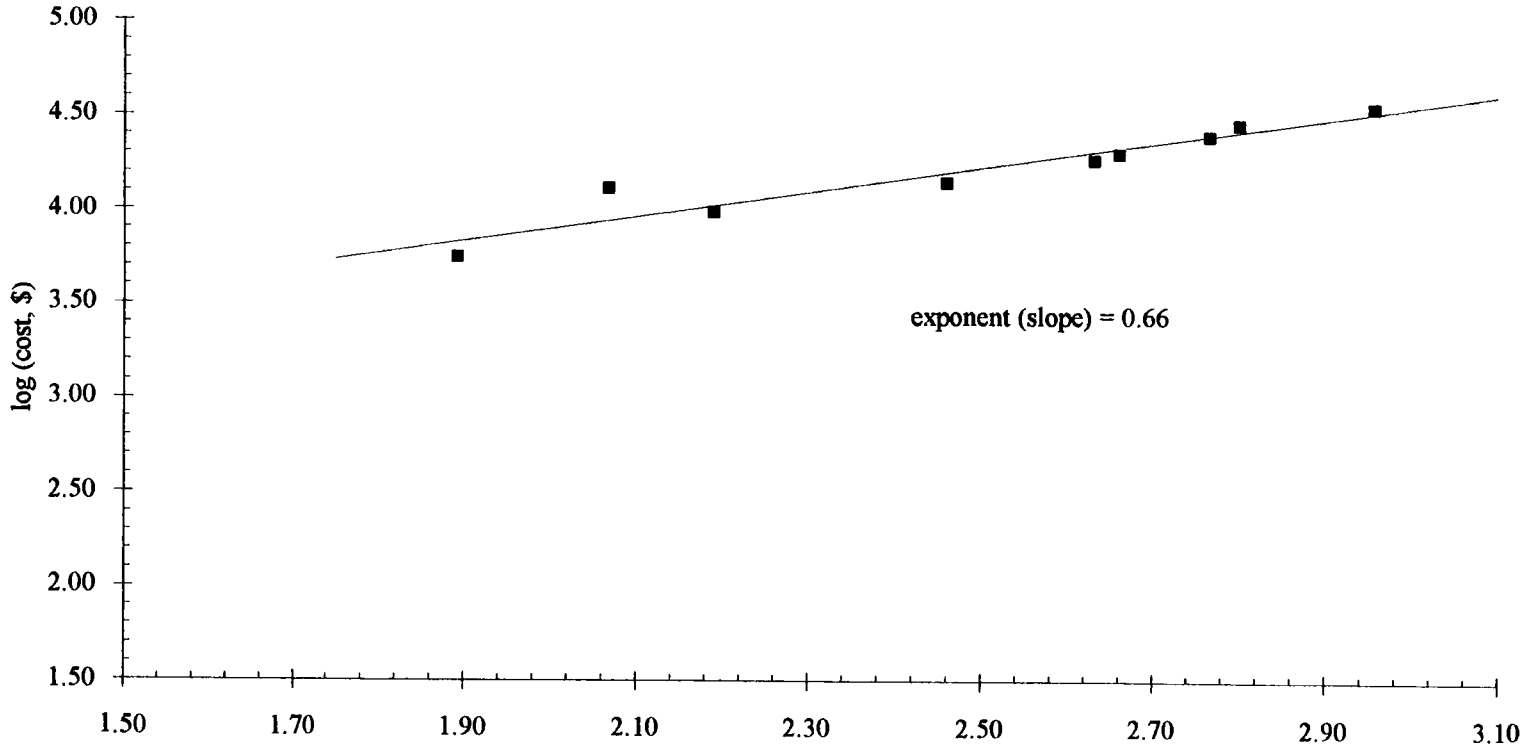

Figure 4.4 Log-Log Plot of Batch Cabinet Spray Washers (1995)

Table 4.4 Cleaning Equipment Scaling Exponents

Equipment	Exponent
stainless steel immersion tanks	0.30
carbon steel immersion tanks	0.57
carbon/stainless steel immersion tanks	0.60
Batch cabinet spray wash equipment	0.66

The exponents determined for carbon steel immersion tanks, carbon/stainless steel immersion tanks, and batch cabinet spray wash equipment show that they may be suitable candidates for application of the sixth-tenths rule for determining order-of-magnitude cost estimates. However the exponent determined for stainless steel was 0.30 suggesting that the use of the six-tenths rule would result in considerable errors for estimating the cost of stainless steel immersion tanks.

The model for batch cabinet spray wash equipment shown as Equation (2) used the total volume of the equipment, reservoir volume and spray chamber volume, as the primary design variable. Initially, it was attempted to develop the model as a function of spray chamber volume only. This was attempted because this variable relates directly to the work package size. However as can be seen in Table 4.5, spray chamber volume does not correlate well with the cost of the equipment. Table 4.5 lists the specifications available for this type of equipment based upon the literature of four equipment vendors. None of the possible design variables considered correlate well with the cost of the equipment with the exception of total equipment volume previously described as the summation of reservoir volume and spray chamber volume. This could be seen in Figure 3.6. A general relationship is seen to exist between spray chamber volume and reservoir volume. In Table 4.5 this relationship is seen to vary from 1:1 to 4:1.

Table 4.5 Batch Cabinet Spray Wash Equipment Specifications

Top-Loading

Reservoir Volume	Spray Chamber				Pump			Turntable capacity
gallons	Height, in	Diameter, in	Volume, ft3	gal	hp	pressure, psi	flowrate, gpm	lbs, upper/lower
18	22	21	4	30	1	40	20	500
34	30	29	11	83	2	45	35	500
40	18	24	5	38	3	45	60	1000
60	28	30	11	83	3	45	60	1000
90	40	35	22	166	5	50	120	1500
125	29	37	18	136	5	60	100	1000
135	40	47	40	302	5	55	120	1500
140	36	60	59	445	10	60	190	2500
150	36	50	41	309	10	55	190	2500
180	31	47	31	234	7.5	60	150	1500
190	42	60	69	520	10	55	200	2000
240	33	60	54	407	10	60	200	2000
265	52	72	123	928	10	60	220	2500
320	33	72	78	588	10	60	200	2000

Front-Loading

65	36	27	12	91	5	50	130	300/700
75	33	27	11	83	3	52	55	500
75	36	27	12	91	2	40	50	500
85	48	35	27	204	5	50	130	400/1500
105	54	42	43	324	10	60	190	500/2000
125	40	37	25	189	5	60	100	1000
175	38	29	15	113	5	80	85	1000
180	60	47	60	453	10	60	200	2000
180	60	50	68	513	15	60	270	500/2000
200	52	39	36	272	7.5	75	120	1500

The pump capacity and reservoir volumes shown in Table 4.5 counter the recommended sizes as espoused by the ASM Committee on "Selection of Cleaning Process" [27]. It is their recommendation that reservoir volumes be at least three times the capacity of the pump expressed in volume per minute. This was recommended to allow ample time for solids and foam to settle. However as can be seen in Table 4.5 this is clearly not the case. Moreover than not, the reservoir volumes of batch spray wash equipment has less than a 1:1 ratio with pump capacity. This fact suggests that parts being cleaned may be sprayed with an emulsified mixture of water, cleaner, and soil due to inadequate settling of the wash solution.

5.0 ESTIMATED ANNUALIZED OPERATING COSTS

The various process design considerations discussed in Section 2.0 of this thesis were estimated for a proposed industrial cleaning system. A flow diagram of the proposed system is shown in Figure 5.1. As shown in Figure 5.1, the proposed process is semi-aqueous with one wash and two rinse stages. The first two stages utilize ultrasonics as the form of agitation. The equipment models of Section 3.2 were used to predict the cost of this wash and rinse equipment. Data taken in support of the Alternative Solvents: Cleaning, Testing, and Evaluation Project was used to select the wash agent and provided the data necessary for mass balance calculations. This data is shown in Appendix B. Immersion tanks were sized and the model for stainless steel tanks, introduced in Section 3.2 as Equation (1a) along with the ultrasonics option model shown as Equation (1d), were used to predict their cost. These cost estimates are shown in Table 5.1. Table 5.1 also includes an estimate of amortization for the cost of purchase the tanks at an interest rate of 10 per cent over eight years. It also includes an estimate of the depreciation (straight line method). Information contained in vendor literature of such equipment was then used to complete the estimation of operating costs. Table 5.2 provides a summary of the data used to calculate annualized operating cost for the proposed immersion system. The calculations used to derive the data of Table 5.2 are found in Appendix C and serve to illustrate some of the design considerations mentioned in Section 2.1 of this thesis. Table 5.3 completes the estimate of annualized operating costs by including such cost estimates as labor and overhead as a per cent of the total direct costs as shown [1]. This is the typical procedure for estimating these costs in the chemical process industries.

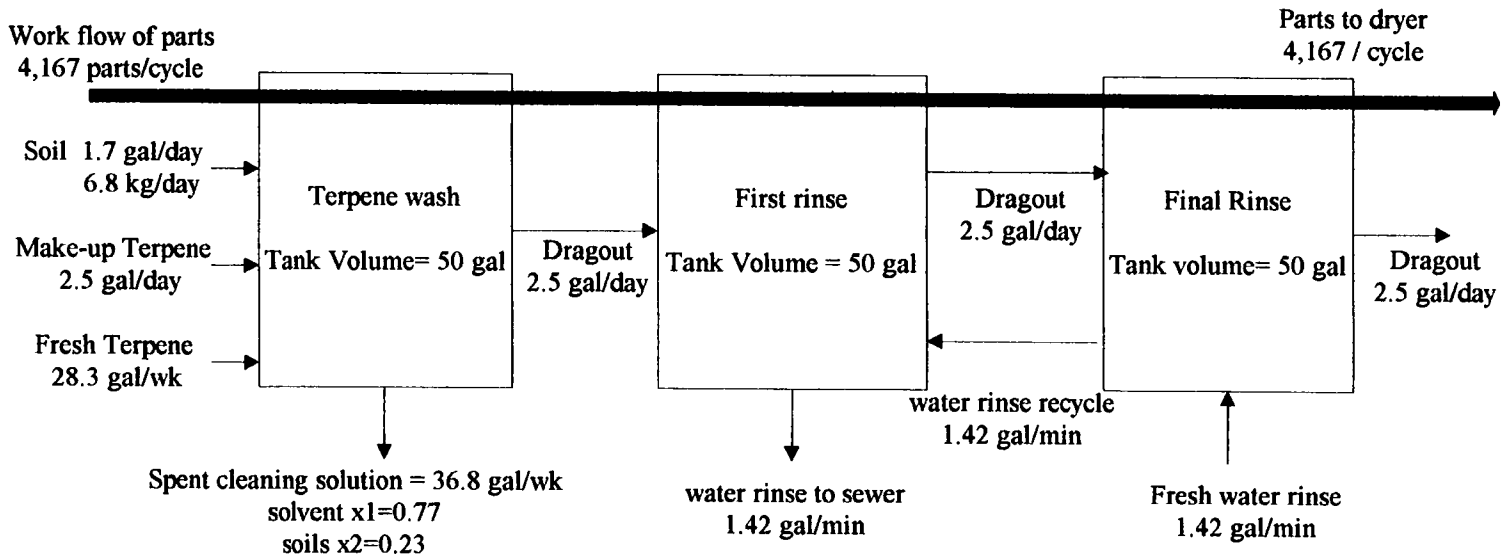

Figure 5.1 Flow Diagram for Proposed 3 Stage Immersion Process

Table 5.1 Estimated Wash and Rinse Tank Costs

Wash Tank

1	Volume	50 gallons
2	Materials of construction	stainless steel
3	Cost (equation 1a)	$4,225
4	Ultrasonics cost (equation 1d)	$4,850
5	Vapor extraction (Table 2.4.2)	$1,100

Emulsion Rinse Tank

1	Volume	50 gallons
2	Materials of construction	stainless steel
3	Cost (equation 1a)	$4,225
4	Ultrasonics cost (equation 1d)	$4,850

Final Rinse Tank

1	Volume	50 gallons
2	Materials of construction	stainless steel
3	Cost	$4,225

Tank Installation

1	Installation cost (equation 1g)	$3,696

Total cost of installed tanks **$27,171**

Amortization

1	Annual simple interest rate	10%
2	Payback period	8 years
3	Cost of capital	$21,737
4	monthly payment	$510
5	yearly payment	$6,114

Depreciation

1	Method of calculation	straight-line
2	Estimated service life	8 years
3	Estimated salvage value	$300
4	Annual depreciation	$2,897

Table 5.2 Cleaning Process Data

Part Details

1	Diameter	0.094 inch
2	Surface area	1.15 in2/part
3	Volume	0.029 in3/part
4	Mass	3.38 grams/part

Part Throughput

5	Daily production	300,000 parts / day
6	Days operation per year	250 days / year
7	Cleaning cycles per hour	3 cycles / hour
8	Hours per day in operation	24 hrs / day
9	Throughput	4,167parts/cycle
10	Part volume per cycle	0.52 gal/cycle
11	Total surface area	33.34 ft2/cycle
12	Mass	14.1 kg or 31 lbs/cycle

Soil

13	Soil per part	2800 mg/ft2
14	Total soil introduced	93.34 g/cycle or 0.62 lbs/hr

Process Details

15	Total cycle time	20 minutes/cycle
16	Dragout	0.104 gal/hr or 2.5 gal/day
17	Rinse/sewer water	1.42 gal/min, 2038 gal/d , 270 ft3/d
18	Displacement volume of parts	0.52 gal/cycle
19	Sewer costs	$679 / year
20	Evaporative losses	0.63 lbs/day or 0.09 gal/day
21	Make-up terpene required	2.5 gal/day
22	Rinse water costs	$521 / year
23	Soil loading bv/week	0.3
24	Displacement volume by soil	8.5 gal/week or 441 gal/yr
25	Start-up terpene	28.3 gallons
26	Change-out terpene	28.3 gallons/week
27	Yearly terpene usage	2068 gal/yr
28	Cost terpene	$20.25 /gal or $41,877/yr
29	Cost to dispose of terpene	$225/55gal or $7,527/yr

Electrical Details

30	KUB supplied electricity	0.055 kW/hr
31	Total electrical utilities	1,945 /yr
32	Power requirement	5,894 watts

Table 5.3 Estimated Annualized Operating Costs

Total Direct Costs

1	Raw materials (terpene)	$41,877
2	Utilities: electricity	$1,936
3	process rinse water	$521
4	sewer	$679
3	Direct Labor(DL) @ $14/hr	$84,000
4	Supervision @ 15% DL	$12,600
5	Maintenance @ 6% FCI	$1,409
6	Operating supplies@15% Main	$211
7	Waste liquid terpene disposal	$7,527
	Total Direct Cost	**$150,760**

Total Indirect Costs

1	Payroll overhead @ 25% DL	$21,000
2	Stores & supplies @ 20% DL	$16,800
3	Quality control @ 25% DL	$21,000
4	Depreciation	$2,380
	Total Indirect Cost	**$61,180**

Estimated Annualized Operating Costs	**$211,940**
Cost To Clean Each Part	**$0.0028 / part**

6.0 CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

In this thesis, three cost models were proposed to estimate the costs of dual wall immersion tanks. The models differed on the materials of construction. Additionally, eight primary equipment options for immersion tanks were identified and also cost modeled. From the immersion tank option models, the cost of ultrasonics was determined to be the most expensive option. The cost model presented for the ultrasonics option, Equation (1d), projected the cost of ultrasonics as 8.8 times the cost of a basic immersion tank constructed of carbon steel and 3.9 and 2.8 times the cost of tanks of combined materials and stainless steel, respectively. As these models confirm, the ultrasonics option can represent a significant increase to the cost of immersion equipment. Therefore, the selection of ultrasonic equipment is not one that should be taken lightly and instead should be application specific. Mechanical forms of agitation such as impeller agitation or platform lift also represent significant additions to the cost of immersion equipment. However, their cost was determined to be roughly 25 per cent of the cost of the ultrasonic option. Three commercially available immersion tanks were selected in which to compare cost model predictions with the actual vendor quotes. The first tank was constructed of both carbon and stainless steel and had three primary options. These options were an oil skimmer, mechanical agitation, and rotating basket mechanism. The model predicted the cost within 12 per cent of the actual vendor quote. The second and third tanks were constructed of carbon steel and had only mechanical agitation as an option. For these tanks, the cost models predicted the cost of the tanks within ten and one per cent. Thus, these examples illustrated the potential of the models for deriving cost estimates of study quality for the purpose of preliminary process design.

The cost of batch cabinet spray wash equipment was also modeled. This model is applicable for both top and front-load equipment configurations. To use the cost model for the batch cabinet spray wash equipment required that both the spray chamber volume and reservoir volume be known.

6.2 Future Work

There are many areas within the industrial cleaning arena which will benefit from continued research and investigation. Potential areas of research include the mechanisms of cleaning, soil/wash agent solubility studies, soil/wash agent separations, and continued equipment cost modeling. Immediate future work may be found in the incorporation of the material contained in this thesis to the Solvent Alternatives GuidE (SAGE) computer program. This may include the calculations to determine vessel sizing, estimations of dragout volume, and equipment cost. This would serve to make the SAGE program a more complete tool thereby increasing its' value to the user.

The models presented in this thesis represent two primary equipment configurations, immersion tanks and batch cabinet spray washers. However, several industrial cleaning equipment configurations remain to be investigated. These include overhead and belt conveyorized open-air spray equipment suitable for aqueous and emulsion technologies, and multistage equipment such as power washers which are also suitable for aqueous cleaning processes. Cost models for this equipment could expand the versatility of the SAGE program even further.

In addition, chemical and physical separations will play a much greater role in all three technologies. Therefore research to identify the different technologies available to perform separations and determination of the typical separation efficiencies that could be expected would be valuable to the continued development of each alternative. This is

particularly so with semi-aqueous and hydrocarbon immersion processes. As illustrated in the calculations of Appendix A, the potential for recycle and re-use will have a major impact on the continued selection and viability of these alternatives.

Although the model presented here for immersion tanks may be useful in some instances, its' continued improvement will be realized with continued attention given the models of the individual process options. This will be realized by the further collection of cost data. Furthermore, the drying stage, neglected in this thesis, will require attention as this is often a necessary stage in all three alternative processes. Therefore it is suggested that cost data be collected on dryers and that a cost model be developed.

Future work may also include the development of correlations between cost and the levels of cleanliness desired for particular applications. This type of research will require a close relationship with an industrial partner or a specific industry.

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APPENDICES

APPENDIX A

Rinse / Dragout Calculations

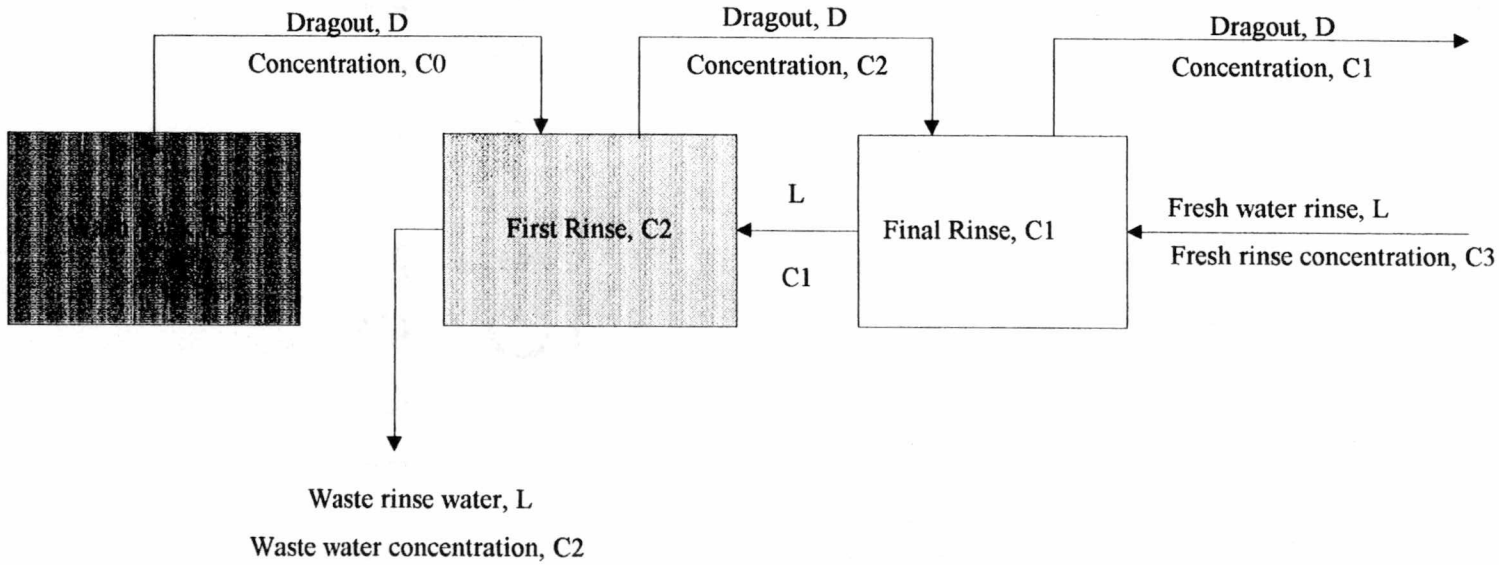

Figure A-1. 3 Stage Aqueous Cleaning Process

Example 1

Determine the final rinse concentration (C_1) and the fresh rinse water flow rate (L) based upon the following process operating conditions.

Fixed process variables:

Dragout, D = 2 gal/hr

Initial Wash concentration, C_0 = 30 oz/gal

First rinse concentration, C_2 = 0.1 oz/gal

Fresh rinse concentration, C_3 = 0.0 oz/gal

Assuming steady-state operation

A component mass balance around rinse tanks 1 and 2 yields Equations (1) and (2):

Tank 1: $DC_0 + LC_2 = DC_1 + LC_1$ (1)

Tank 2: $DC_1 + LC_3 = DC_2 + LC_2$ (2)

We now have 2 equations and 2 unknowns, L *and* C_1:

Solving Equation (1) for C_1 *yields Equation (3):*

$$C_1 = (DC_0 + LC_2) / (D + L) \quad (3)$$

Substituting Equation (3) into Equation (2) yields Equation (4):

$$D\,[(DC_0 + LC_2) / (D + L)] + LC_3 = DC_2 + LC_2 \quad (4)$$

Equation (4) results in a second-order quadratic equation with respect to L:

$$C_2L^2 + (DC_2)L + D^2(C_2 - C_0) = 0$$

This is solved using the quadratic formula: $[-b \pm (b^2 - 4ac)^{1/2}] / 2a$

This yields the needed fresh rinse flowrate to keep $C_2 = 0.1$ oz/gal:

$$L = [-0.2 \pm (0.04 - [4(0.1)(-119.6)]^{1/2}] / 2\,(0.1) = 33.6 \text{ gal/hr}$$

Substituting L back into Equation (3) yields the concentration of the first rinse tank:

$$C_1 = 1.8 \text{ oz/gal}$$

The procedure shown remains the same in the case of the addition of more rinse tanks. However, the resulting math becomes more difficult as the result of the higher order polynomials derived. Eulers or Runge-Kutta methods or similar would be suitable approaches to finding possible solutions to higher order polynomials [63].

APPENDIX B

ACME Parts, Inc. Alternative Solvents Tests Results

Wash Agent Batch Cleaning Tests: ACME Parts, Inc.

Wash Agent	90% Confidence Intervals Particulates (mg/ft2)	Non-volatile residues (mg/ft2)	Total (mg/ft2)
Terpene	10± 5	7± 14	17± 19
Aqueous alkaline(i)	16± 17	183±126	199±143
Aqueous acidic	102± 82	169± 88	271±170
Dibasic esters	106±145	194±322	300±467
N-methyl2-pyrrolidone	11± 5	10± 9	21± 14
Hydrocarbon	30± 23	6± 10	36± 33
Aqueous alkaline(pw)	80± 33	29± 15	109± 48
1,1,1, Trichloroethane	4± 1	46± 18	50± 19

(i) immersion process

(pw) powerwash machine

APPENDIX C

Calculations

Part Volume:

Volume of part = $\pi r^2 L$

diameter = 3/16 inch, radius = 0.0938 inch

$V = \pi$ (0.0938 inch)^2(1 1/32 inch) = 0.0285 in^3/part

Part Throughput:

Production level is 300,000 parts/day

Assumed 3 - 8 hr shifts/day or 100,000 parts/shift or 12,500 parts/hr

Parts per cleaning cycle = (12,500 parts/hr)/(3 cycles/hr) = 4,167 parts/cycle

Tank Sizing:

Parts per cycle = 4,167 parts/cleaning cycle

Work package volume (Basket size) per cycle = 1,8 gal/cycle

Mass of parts per cleaning cycle = (4,167 parts)(3.38 g/part) = 14.1 kg or 31 lbs /cycle

Displacement Volume per cycle=(0.0285 in^3/part)(4,167 parts/cycle)

=119 in^3/cycle or 0.52 gal/cycle

Desired change-out period = weekly

Soil amount per week = 8.5 gal/wk

Desired soil loading fraction per change-out = 0.30 by volume

Solvent per week required = (soil/wk)/0.30 = (8.5 gal/wk)/0.30 = 28.3 gal / wk

Tank Volume = (28.3 gal/wk + 1.8 gal/cycle + 0.52 gal/cycle + 8.5 gal/wk)(1.25

= 48.9 gallons or 50 gallons

Washing Cycle time:

Assume 3 minute wash and rinse stages

Assume 3 minute hang times to reduce dragout for wash and rinse stages

Wash cycle time = 3 + 3 + 3 + 3 + 3 + 3 + (2 minute total load/unload transfer times)

= 20 minutes/cycle

Rinse Water:

Dragout = 2.5 gal/day

Dragout per cycle = 0.0345 gal/cycle

Rinse tank(s) volume = 28.3 gal

Cleaning cycle time = 20 minutes

Rinse flow rate = (28.3 gal/cycle)/(20 minutes) = 1.42 gal/minute

First rinse concentration = (0.345 gal/cycle)/(28.3 gal/cycle) = 0.0012

Rinse water amounts = (28.3 gal/cycle)(3 cycles/hr)(24 hrs/day) = 2038 gal/day

or 270 ft^3/day

Cost of Rinse Water:

Utility rates (Knoxville Utility Board): water

0-2 ft^3:$5.85, next 8 ft^3: $2.04, next 90 ft^3: $2.33, next 300 ft^3: $1.67

Volume of rinse water = 2038 gal/day or 270 ft^3/day

Cost of rinse water = ($5.85)(2)+($2.04)(8)+($2.33)(90)+($1.67)(170) = $521

Cost of Sewer disposal:

Utility rates (Knoxville Utility Board): sewer

0-2 ft^3:$6.85, next 8 ft^3: $3.07, next 90 ft^3: $2.72, next 300 ft^3: $2.33

Cost of sewer disposal = ($6.85)(2)+($3.07)(8)+($2.72)(90)+($2.33)(170) = $679

Work Package (Basket) Volume per cleaning cycle:

Parts cleaned per cleaning cycle = 4,167

Total volume per part = 0.0285 in^3

Total volume of parts cleaned = (4,167 parts)(0.0285 in^3/part) = 118.8 in^3/cycle

Estimated total displacement by parts and cylindrical basket as 350% volume of parts

Displacement volume of parts/basket per cleaning cycle=(3.5)(118.8 in^3)=415.8 in^3/cycle

= 1.8 gallons / cleaning cycle

Soil Contaminant:

Surface area of one part = 0.008 ft^2

Total surface area of parts per cleaning cycle = (4,167 parts)(0.008ft^2/part)

= 33.34 ft^2 /cleaning cycle

Soil contamination per part = 2800 mg / ft^2

Total intrinsic waste introduced to wash tank = (33.34 ft^2 /cleaning cycle)(2800 mg/ft^2)

= 93.34 g / cycle or 0.62 lbs / hr

= 6.8 kg/day or 1.7 gal/day

Dragout Calculations:

Volume of bore = $\pi r^2 L$

Diameter = 1/8 inch, radius = 1/16 inch

V = 0.0127 in^3 or 7.323×10^{-6} ft^3

Parts per cleaning cycle = 4,167 /cycle

Total hole volume per cleaning cycle V_t = (4167 parts)(7.323×10^{-6} ft^3) = 3.05×10^{-2} ft^3

= 0.23 gal

Assumed dragout of 15% of V_t: V_d = (.15)(.23 gal) = 0.0345 gal / cycle

or 0.1035 gal / hr or 2.5 gal / day

Cost of spent solvent disposal:

Spent terpene waste = 1840 gal/year

Disposal cost = $225/55 gal

Cost of disposal = (1840 gal/year)($225/55 gal) = $7,527

Make-up terpene required:

Make-up terpene = (terpene lost to dragout) + (terpene lost to evaporation)

= (2.5 gal/day) + (0.09 gal/day) = 2.6 gal/day

Evaporative terpene losses in wash tank:

Dimensions of wash and rinse tanks are 21x18x30 inches deep

Total air/liquid interface surface area of each tank = 2.63 ft^2

Total air / liquid interface surface area of process = (1 tank)(2.63 ft^2 each) = 2.63 ft^2

Evaporative losses for terpenes at 20 °C = 0.01 lb / hr / ft^2

Total evaporative losses = (0.01 lb/hr/ft^2)(2.63 ft^2)(24 hrs/day) = 0.63 lbs / day

Terpene Loading Calculations:

Soil contaminant entering wash tank = .62 lbs/hr or 74.4 lbs/week or 33.8 kg/week

Terpene density = 844 kg/m^3 or 3.2 kg/gal

Volume of terpene in wash tank = 28.3 gallons

Mass of terpene in wash tank = (28.3 gallons)(3.2 kg/gallon) = 91 kg

Weight fraction of soil contaminant to terpene in wash tank per week

(33.8 kg/week)/(91 kg/week + 33.8 kg/week) = 0.27 or 27%

Mass Ratio of soil contaminant to terpene in wash tank at end of each week

(33.8 kg/week)/(91 kg/week) = 0.37 or 37%

Soil Loading by volume per week = (8.5 gal/wk)/(28.3 gal/wk) = 0.30 or 30%

Displacement Volume by soil contaminant:

Mass of soil contaminant per week = 33.8 kg/week

Density of soil contaminants: brass density = 8400 kg/m^3 or 31.8 kg/gal

cutting oil density = 900 kg/m^3 or 3.4 kg/gal

Estimated mass ratio of soil contaminant = 5 oil : 1 brass fine

Estimated amount of brass fines in terpene = (33.8 kg/week) / 6 = 5.6 kg/week

Estimated amount of oil in terpene = (33.8 kg/week) -(5.6 kg/week) = 28.2 kg/week

Calculated volume of brass fines per week=(5.6 kg/week) / (31.8 kg/gal)= 0.18 gal/week

Calculated volume of oil per week = (28.2 kg/week) / (3.4 kg/gal) = 8.3 gal/week

Calculated volume of soil per year=((8.3 gal/wk) + (.18 gal/wk))(52 weeks) = 441 gal/yr

Terpene Calculations:

Initial start-up terpene = 28.3 gallons

Weekly change out terpene = 28.3 gallons

Daily make-up terpene = 2.5 gallons/day

Yearly terpene usage = 28.3 + (28.3 gal/week)(50 weeks) + (2.5 gal/day)(250 days/yr)

= 2068 gal / yr

Terpene Waste Calculations:

Calculated volume of oil per week = 8.3 gal / week

Calculated volume of brass fines per week = 0.18 gal/week

Volume of waste terpenes per week = 28.3 gal/week

Total disposal volume=(28.3 gal/week)+(.18 gal/week) + (8.3 gal/week) = 36.8 gal/week

Total spent terpene waste = (36.8 gal/week)(50 weeks/yr) = 1840 gal/yr

Electrical Equipment and Power consumption calculations:

40 kHz Ultrasonic generator	8 amp	@120 volts =	960 watts
1/4 hp Recirculation pump motor	5.2 FLA	@120 volts =	624 watts
1/4 hp vapor vacuum pump motor	5.2 FLA	@120 volts =	624 watts
1 hp Dryer motor	13 FLA	@120 volts =	1495 watts
1 hp Exhaust motor	13 FLA	@120 volts =	1495 watts
1 hp rotating basket gear motor	4.8 FLA	@120 volts =	576 watts
Control Equipment	1 amp	@120 volts =	120 watts

*FLA = Full Load Amps

Estimated power consumption = 5894 watts/year

Electrical Utility costs per year:

Assumed 250 workdays / year

Assumed 24 hr / day operation

KUB supplied electricity = $0.055 / kw hr

(5,894 watts)(1 kw/1000 watts)($.055 /kw hr)(24 hr/day)(250 days/year)

Total electrical utilities = $1,945 / yr

Estimated Equipment Costs

Wash tank of stainless steel = 34(50 gallons) + 2500 = $4,225

Ultrasonic option = 97(50 gal) = $4,850/tank (2 tanks) = $9,700

Vapor extraction option (Table 2.4.2) = $1,100

Rinse tank = 34(50 gal) +2500 = $4,225/tank (2 tanks) = $8,450

Total tank cost = ($4,225) + ($9,700) + ($8,450) + ($1,100) = $23,475

Cost of Installation

Cost of tanks (Equation 1c) = (3 tanks [25(50 gal) + 1310]) + [2 tanks (97)(50gal)]

+ $1,100 = $18,480

Cost of installation (Equation 1g) = 0.2 ($18,480) = $3,696

Annual Operating Costs

Start up terpene = 28.3 gallons

Change-out terpene weekly = 28.3 gallons/wk

Yearly terpene usage = 2068 gallons

Cost of terpene = $20.25 /gal

Yearly cost of terpene = ($20.25/gal)(2068 gal) = $41,877 /yr

Yearly cost of disposal = ($225/55 gal)(2025 gal) = $7,527 /yr

Workdays in year = 250 days/yr

Annualized operating costs = ($41,877)+($7,527)+($1,936) + ($84,000) + (12,600)

+ ($1,384) + ($208) + ($21,000) + ($16,800) + ($21,000) + ($2,380) = $211,940 /yr

Number of parts cleaned = 300,000 /day

Cost per part = ($211,940 /yr)/(300,000 parts/day)(250days/yr) = $0.0028 /part

Amortization

Annual simple interest rate = 10 %

Payback period = 8 years

Amount borrowed = $27,171

Cost of capital = ($27,171)(.1 / yr)(8 yrs) = $21,737

Total due = ($27,171) + ($21,737) = $41,515

Yearly payment = [($23,064) + ($18,451)] / 8 years = $6,114 / year

Monthly payment = $6,114 / 12 months = $510 / month

Depreciation

Straight-line method

Original value of tanks = $23,475

Expected Salvage value = $300

Tank lifetime = 8 years

Depreciation = [($23,475) - ($300)] / 8 yrs = $2,897 / year

VITA

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