Development of the Metal Finishing Facility Risk Screening Tool (MFFRST)

by William M. Barrett Jr* & Paul Harten

Recently, the US Environmental Protection Agency completed the development of the first version of the Metal Finishing Facility Risk Screening Tool (MFFRST) and has made this product available to the general public (http://www.epa.gov/ncea/mffrst.htm). MFFRST calculates the air emissions from a metal plating line and estimates the risk to both facility employees and the surrounding neighborhood from the air emissions. The next step in the development of MFFRST is to include solid and liquid wastes in the analysis. In order to accurately estimate the risks associated with these waste streams, the quantity of waste generated and the mass of hazardous substances they contain must be known. The second version of MFFRST will utilize process synthesis and integration techniques to simulate the metal finishing process. Process synthesis and integration devolve the process into simple structures that can then be combined to create a model of the metal plating line. The quantity and composition of waste streams can then be calculated using the model. The model can then be used to analyze the effect of process modifications on waste generation. The ultimate goal of the program is to enable the user to evaluate the process to analyze any of a number of factors, including quantity and composition of wastes generated, cost/benefit analysis of waste reduction processes and/or life cycle analysis of the metal finishing process.

Facility workers and individuals in the community surrounding plating facilities are exposed to a variety of chemicals used within the plating process. The United States Environmental Protection Agency, as part of the Common Sense Initiative, created the Metal Facility Risk Screening Tool (MFFRST),[1] which is now available for download from the EPA's website (http://www.epa.gov/ncea/mffrst.htm). MFFRST estimates air emissions from metal finishing processes and determines the risk to persons as a result of these emissions. The first part of this paper describes the emissions models and risk estimation procedure utilized in MFFRST.

During the 2000 review of EPA's metal finishing sector research and development plan, the emissions and risk characterization aspect shifted from emissions controls and other end-of-pipe approaches to demonstration of alternative materials and pollution prevention. As a result of this shift, MFFRST is being updated to become a tool that will not only characterize risks to employees and the environment, but will also consider cost-effective pollution prevention solutions. The second half of this paper discusses pollution prevention methodologies available for implementation in a future version of MFFRST that is currently being developed.

Fig. 1—Screen shot of MFFRST Version 1 decorative chromium plating line.

Summary of MFFRST Version 1

EPA has completed development of and has released to the public, the first version of MFFRST. MFFRST is a user friendly computerized screening tool that allows anyone to easily evaluate the emissions, potential exposures and health risks to workers and nearby residents from a nearby metal finishing facility.[2] MFFRST attempts to characterize some of the major line processes and quantify the emissions of the most important contaminants (particularly those that are likely to exhibit some toxicity).[3]

Nuts & Bolts: What This Paper Means to You

The US EPA has been working hard at developing computer programs to calculate air emissions from plating lines and then estimate the risks. This paper shows how they work and discusses the next phase, where solid and liquid wastes are included in the analysis. In the end, you can analyze any number of factors, and learn that addressing the emissions could actually save money in the long run … a win-win scenario.

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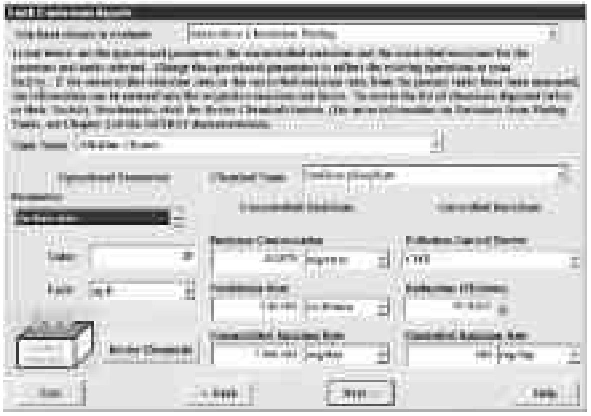

Fig. 2—MFFRST tank emissions input screen for decorative chromium plating process.

Table 1
Processes Analyzed by MFFRST Version 1

Electrolytic Processes	Non-Electrolytic Processes
Hard Chrome Plating	Hexavalent Chromium Passivation
Decorative Chromium Plating	Anodizing Sealer
Trivalent Chromium Plating	Electroless Nickel Plating
Nickel Plating	Acid Etch for Zinc Plating
Sulfuric Acid Anodizing	Bright Dip Zinc Plating
Chromic Acid Anodizing	Alkaline Cleaning
Gold Plating	Acid Etch/Desmut
Copper Strike	Phosphate Coating
Copper Cyanide Plating	Chromate Conversion
Acid Copper Plating	Solvent Degreasing
Cadmium Plating	
Zinc Cyanide Plating	
Zinc Chloride Plating	

MFFRST is a risk screening tool. As a screening tool, only simple models requiring a minimum of site-specific information were implemented to evaluate a site.[4] The emissions, fate and transport models implemented in MFFRST include conservative assumptions. A screening model is used to identify potential problems so that they may be more thoroughly evaluated using more complex models and/or measurements of field conditions.

Environmental risk assessment is a multi-step process, which includes characterization of the source, modeling contaminant transport from the source to the receptor and determination of likely health effects of the contaminant on the exposed population. The following sections describe the emissions rate, exposure assessment and health risk assessment methods used by MFFRST.

Source Characterization

MFFRST v.1 characterizes 15 different plating line processes (Table 1), broadly grouped into two categories, electroplating/electrolytic processes and non-electrolytic processes. The program estimates emissions for 22 contaminants (Table 2). The source can be characterized using either Toxic Release Inventory (TRI) data, a generic model of the plating process or site-specific process or emissions data.[2] The MFFRST screen for a chromium plating line is shown in Fig. 1. Default parameters can be replaced with site-specific parameters using the input screen shown in Fig. 2. Emission rates from hard chromium plating tanks are estimated using the method described in the CSI report, as described below.

Table 2
Contaminants Modeled in MFFRST Version 1[1]

Contaminant	Non-Cancer Risks				Carcinogenic
	PEL, mg/m^3	REL, mg/m^3	TVL, mg/m^3	RfC mg/m^3	Risks Unit Risk (mg/m^3)$^{-1}$
Hexavalent Chromium	—	0.001	0.05	$8x10^{-6}$	12
Sulfuric acid	1	1	1	—	—
Nickel	1	0.015	0.1	—	—
Gold	—	—	—	—	nd
Cyanide	—	—	—	0.07	—
Copper1	1	1	1	—	—
Cadmium	0.005	—	0.01	$2x10^{-4}$	1.8
Zinc	—	—	—	—	—
Sodium Hypophosphite	—	—	—	—	—
Hydrochloric Acid	7	7	—	0.02	—
Nitric Acid	5	5	5	—	—
Sodium Hydroxide	2	—	—	—	—
Sodium Phosphate	—	—	—	—	—
Sodium Metasilicate	—	—	—	—	—
Hydrofluoric Acid	2.5	2.5	—	—	—
Phosphoric Acid	1	1	1	0.01	—
1,1,1-Trichloroethane	1900	1900	1900	2.2	—
Tetrachloroethene	678	—	170	0.04	—
Methanol	260	260	260	2	—
Methyl Ethyl Ketone (Butanone)	590	590	590	1	—
Toluene	750	375	188	0.4	—

Electrolytic Processes

Emissions of metals and other components to the atmosphere from electrolytic (electroplating and anodizing) tanks are proportional to:

- The current density applied to perform the plating operation (CD);
- The inverse of the cathode efficiency (CE); and
- The concentration of the chemical component in the process tank (CC).

Cathode efficiency is the fraction of the applied electrical power that results in the deposition of metal on the substrate. For most processes, the cathode efficiency is greater than 90 percent. However, for hard and decorative chromium plating, the cathode efficiency is typically less than 20 percent. The proportion of the electrical power that does not result in metal deposition is used to decompose water into gaseous hydrogen and oxygen, which contributes to atmospheric emissions. As the hydrogen and oxygen bubbles rise to the surface of the tank and escape into the atmosphere, they can entrain a substantial amount of the plating solution resulting in atmospheric emissions. The rate of gas evolution is a function of the chemical and electrochemical activity occurring in the tank, the

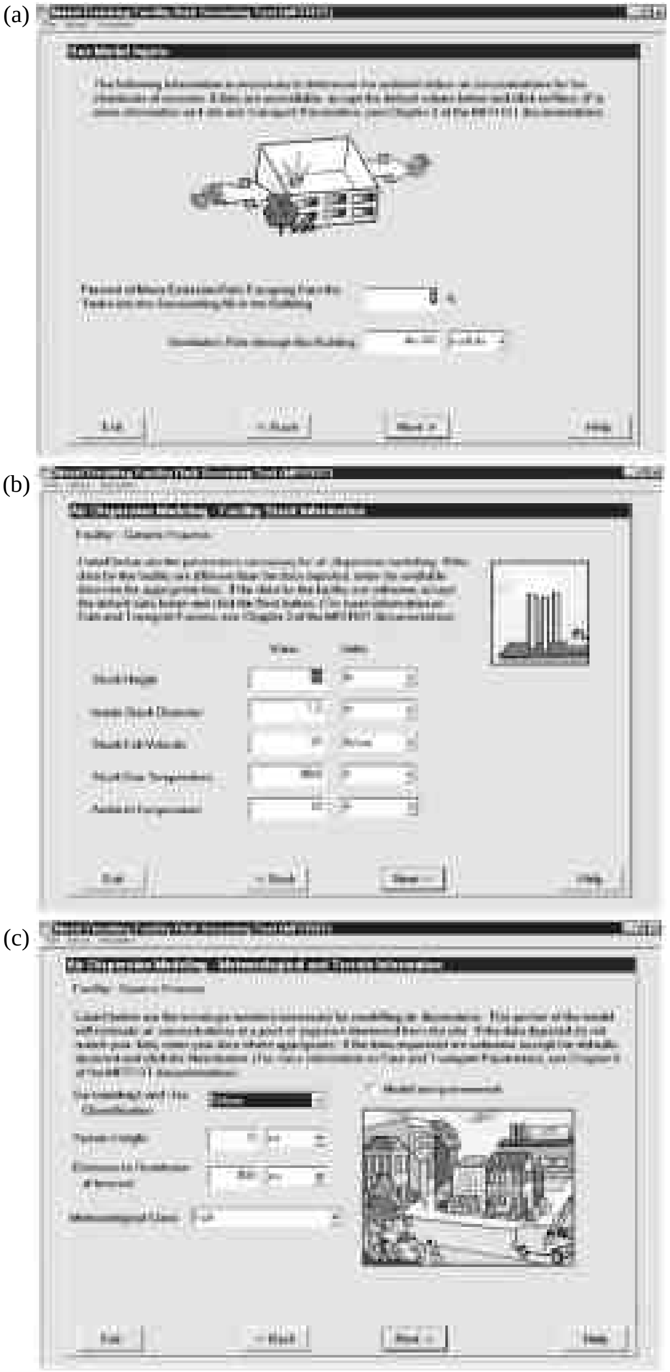

Fig. 3—Exposure model parameter input screens.

strength and temperature of the solution and the current density in the tank. For hard chromium electroplating, the AP-42 chromium emission factor is 7.78 mg/A-hr, and controlled chromium emissions range from 0.0027 to 0.96 mg/dscm.[5] The typical technique used to control emissions from a chromic acid plating tank include add-on control devices and chemical fume suppressants. The most common add-on control devices include mist eliminators and wet scrubbers. The US EPA[5] presents the emissions rates from chromium electroplating processes incorporating these emissions control technologies.

In MFFRST, the emissions from non-chromium electroplating are calculated using the following equation:

$$RC_c = \frac{CC_c CD_c CE_{Cr}}{CC_{Cr} CD_{Cr} CE_c}$$

where:

RC_c = concentration of the contaminant over the plating bath relative to the concentration of hexavalent chrome
CC_c = concentration of the contaminant in the plating bath
CC_{Cr} = concentration of the hexavalent chromium in the plating bath
CD_c = current density of the plating bath
CD_{Cr} = current density of the hexavalent chromium plating bath
CE_c = cathode efficiency of the contaminant plating bath
CE_{Cr} = cathode efficiency of the hexavalent chromium plating bath

MFFRST emissions estimates for inorganic compounds assume that all emissions from tanks are controlled by the facility's air pollution control devices. This assumption appears to lead to a discrepancy with Toxic Release Inventory (TRI) data for plating facilities.[1] For example, TRI data indicate that the average cadmium emission from six facilities was 89.2 lb./yr, compared to 0.0245 lb./yr estimated by MFFRST. Schwartz and Lorber[6] conducted a follow-up study to compare emissions predicted by MFFRST with actual air emissions from operating plating facilities that utilize air pollution control devices. Stack test reports for 12 facilities were used in the model validation exercise. The study indicated that the MFFRST emissions estimates were a factor of 5.7 below the actual emissions observed. Differences in the emissions estimates from the actual emissions rates were attributed to small differences in the removal efficiency of the air pollution control device. That is, the difference could be explained by adjusting the removal efficiency of the air pollution control device from the default value of 99.95 percent to 99.5 percent.

Non-Electrolytic Processes

The emissions from non-electrolytic tanks are determined based on the assumption that emissions are the result of turbulence caused by the use of compressed air to mix the tanks. As the mechanical agitation of mixing causes the emissions, tanks that are not mixed do not emit any of the inorganic compounds because little or no volatile materials are present in the electroplating process tank. Emissions from tanks not required by occupational safety regulations to be vented outside the plant (*e.g.* acid etch/bright dip processes and phosphate coating) are released into the air within the plant and exit the plant into the surrounding community as fugitive emissions. Emissions from tanks mixed with air are calculated using the following equation:[5]

$$E = \frac{1.9\sigma}{R_b}\left[\frac{(1\text{-}2a\text{-}9a^2)^{0.5} \;\; +(1\text{-}a)}{(1\text{-}3a) - (1\text{-}2a\text{-}9a^2)^{0.5}}\right]^{0.5}$$

where:

E = emissions factor in grains per cubic foot of aerated air
ƒã = surface tension of the bath in pounds force per foot (lbf/ft)
R_b = average bubble radius, inches
a = $\frac{0.0072R_b}{\sigma}$

In the above equation, physical properties and unit conversion factors are incorporated into the constants, resulting in a dimensionally consistent equation. The above equation is used for tanks without emissions controls. For tanks that have emissions control, the emission rate is multiplied by the ratio of emissions from the chromium electroplating line with controls to the emissions of the chromium electroplating line without controls.[3] This ratio would represent the fraction of the contaminant emitted by employing this emission control technology.

Solvent Vapor Degreasing

Solvent vapor degreasing is the only non-aqueous process considered in MFFRST. Solvent vapor degreasing is an effective process for removing residual oils and greases to improve adherence of the electroplated metal to the part. AP-42 states that solvent emissions are best estimated by reviewing solvent purchase records. Solvents are volatile, and new solvent is purchased to replace solvents lost through evaporation from the degreasing operation.[5] When information is not available for solvent purchases, the emissions factors in Table 3 can be used. Emissions control devices can reduce vapor emissions between 20 and 60 percent. Modifying operating procedures can reduce emissions 15 to 40 percent. The total reduction in emissions from a vapor degreasing unit through a combination of emissions control devices and modifying operating procedures ranges from 30 to 75 percent.[5]

The emissions estimated by MFFRST for volatile organic compounds are very similar to emissions reported in the TRI.[1]

Table 3
Solvent Loss Emissions Factors for Degreasing Operations.[5]

Type of Degreasing	Activity Measure	Uncontrolled Organic Emission Factor
All	Solvent Consumed	1000 kg/Mg2000 lb/ton
Cold Cleaner		
Entire Unit	Units in Operation	0.300 Mg/yr/unit 0.33 tons/yr/unit
Waste Solvent Loss		0.165 Mg/yr/unit 0.18 tons/yr/unit
Solvent Carryout		0.075 Mg/yr/unit 0.08 tons/yr/unit
Bath and Spray Evaporation		0.06 Mg/yr/unit0.07 tons/yr/unit
Entire Unit	Surface Area and Duty Cycle	0.4 kg/hr/m^{2}0.08 lb/hr/ft^2
Open Top Vapor		
Entire Unit	Units in Operation	9.5 Mg/yr/unit10.5 tons/yr/unit
Entire Unit	Surface Area and Duty Cycle	0.7 kg/hr/m^{2}0.15 lb/hr/ft^2
Conveyorized, Vapor		
Entire Unit	Units in Operation	24 Mg/yr/unit26 tons/yr/unit
Conveyorized, Non-boiling		
Entire Unit	Units in Operation	47 Mg/yr/unit52 tons/yr/unit

Risk Characterization

The risk associated with the emissions calculated above is determined for both fugitive emissions into the workplace and emissions from the plant into the ambient atmosphere. The MFFRST input screens used to provide the program with the model parameters is shown in Fig. 3. The exposure scenarios evaluated by MFFRST are the worker's breathing zone and ambient air in the neighborhood surrounding the plating facility.

MFFRST uses the SCREEN3[7] model to calculate the ambient concentrations that an individual residing 100 meters from the facility's stack for a period of 30 years (350 days per year, 16 hours per day) would be exposed.[4] In order to convert the SCREEN3 concentration to an annual average, the calculated concentration is multiplied by a (persistence factor(of 0.08 to account for variations in wind direction and speed.

Exposure data for receptors are entered on parameter input screens shown in Fig. 4. Health risks are screened for both carcinogenic and non-carcinogenic endpoints. For non-carcinogenic endpoints, the hazard quotient (HQ) for each compound is calculated. The hazard quotient is the ratio of the exposure concentration to the chemical's reference concentration. The reference concentration is an estimate of the concentration at which daily exposure to the chemical by the general human population would not result in appreciable risk of deleterious health effects. The sum of the hazard quotients for all of the chemicals emitted is the hazard index (HI). A hazard index greater than one calculated for an exposure scenario indicates potential health risks to individuals.

Cancer health risks for the general population are determined based upon the inhalation unit risk.[8] The inhalation unit risks are an estimate of the relationship between the concentration an individual is exposed to and the probability that the individual will develop cancer as a result of that exposure. The unit risks are upper bound estimates of the cancer risk per unit intake of a chemical over a person's lifetime. Values of the unit risk for the chemicals of concern in MFFRST are listed in Table 2. An individual's cancer risk can be calculated using the following equation:

$$risk = (unit\ risk)\,(C_a)\left(\frac{InhR_a}{0.83\ {}^{m^3}/_{hour}}\right)\left(\frac{EF_a}{365\ {}^{days}/_{year}}\right)\left(\frac{ET_a}{24}\right)\left(\frac{ED_a}{70\ years}\right)\left(\frac{70\ kg}{BW}\right)$$

where:

C_a = the ambient concentration of the contaminant (mg/m^3)
$InhR_a$ = the individual's inhalation rate (m^3/hr)
EF_a = Exposure frequency (days/yr)
ET_a = Exposure time (hr/day)
ED_a = Exposure duration (yr)
BW = Body weight (kg)

Inside the plant, the exposure of workers to chemicals emitted from the process was estimated using a box model. A box model determines indoor air concentrations using a material balance around the building. The material inputs to the material balance are fresh air input and chemical emissions from the tank. The material output is the exhaust from the building. The result of the box model is an average concentration of the chemical within the building. A literature review[4,9] determined that chromium concentrations near the chromium plating tank were 10 times greater than the average chromium concentration in the building. This indicates that exposures for workers who routinely work near the chromium electroplating tank may be underestimated by MFFRST. The concentration of the chemical determined from the model is then compared to either National Institute of Occupational Safety and Health's (NIOSH) Recommended Exposure Limits (RELs), Occupational Safety and Health Administration (OSHA) Permissible Exposure Limits (PELs) or American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs). The results of the model are shown in Fig. 5.

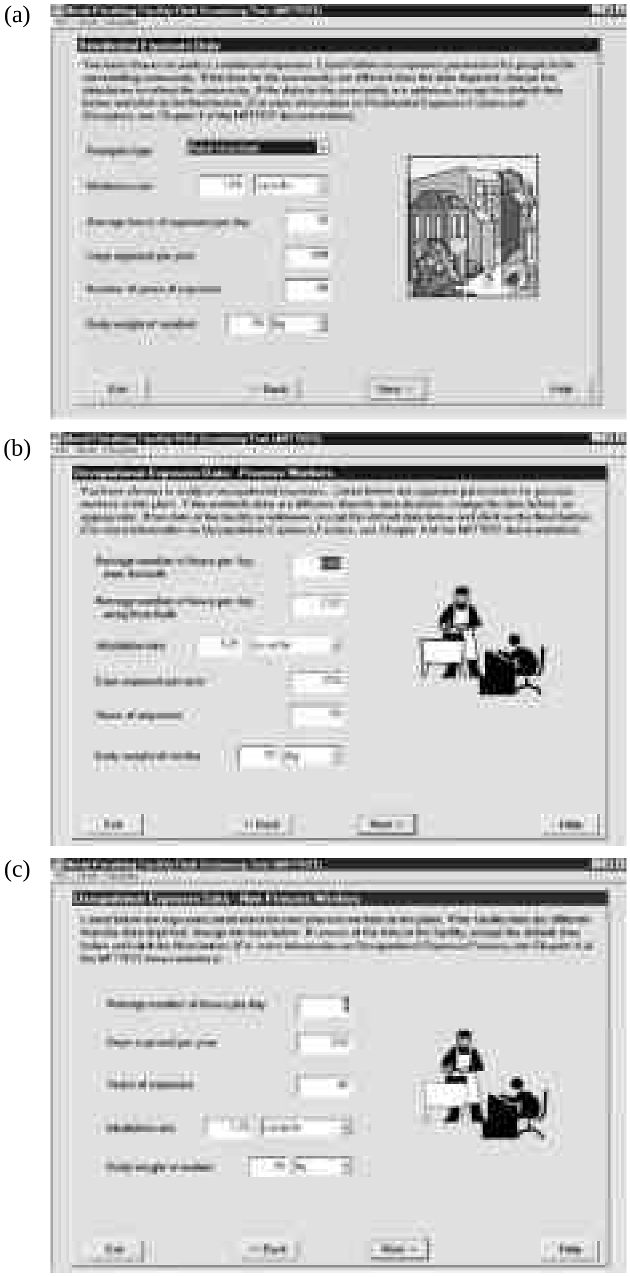

Fig. 4—Exposure scenario parameter entry screen.

Development of MFFRST Version 2

Past research and development in emissions and risk characterization has focused on the development of a risk screening tool to target reduction of risk to workers. As indicated above, the first version of MFFRST is the outcome of these research goals. The 2000 update of the National Metal Finishing Environmental Research and Development Plan[10] identified that the emphasis of emissions and risk characterization R&D shifted from emissions controls and other end-of-pipe approaches to research, development and demonstration of alternative materials, and pollution prevention. Accordingly, MFFRST development is shifting to create a tool that will not only characterize risks to employees and the environment, but will also consider cost-effective pollution prevention solutions.

With the goal of the updated R&D plan in mind, development has begun on a second version of MFFRST. The capabilities of MFFRST will be expanded to include identification of waste generating processes and evaluation of pollution prevention alternatives. Pollution prevention has numerous advantages to the plating facility, including:

- Reduced Environmental Risks - By reducing the total mass of wastes discharged by the facility, the risks to workers and surrounding communities should be reduced, and

- Economic Benefits - Reducing the amount of waste produced reduces waste disposal and improves the utilization of chemicals obtained for the process.

Profitable pollution prevention (P3) is an approach being embraced within industry to find cost-effective technologies and practices for compliance with the regulations.

The goals of development of this expansion of MFFRST is to provide the user with a program that can easily be used to model the plating process and evaluate the effects of modifications to the plating process on the quantity of wastes produced. In order to meet this objective, the model must conduct material balances around each process in the plating line and evaluate potential chemical reactions that may occur within each tank. For example, spent rinse water may be reused at numerous locations within the process. The program will need to evaluate the different reuse possibilities, determine which are feasible and compare the economic aspects of the different reuse options.

Chemical process simulators are being used within the chemical process industry to evaluate pollution prevention options. Process simulation can be effective tools in achieving the objectives of pollution prevention.[11] Currently available process simulators are extremely complex and do not have modules available to simulate the metal finishing process. The second version of MFFRST is envisioned to be an easy-to-use metal finishing process simulator that can evaluate pollution prevention options. The following sections describe different techniques used in pollution prevention in both chemical and metal finishing processes.

Life Cycle Assessment

It is widely recognized that early consideration of environmental matters during design is needed to achieve good environmental performance at least cost.[12] Most processes have demands for both energy and disposal of residues that are met by organizations outside the limits of the process. The product life cycle consists of the acquisition, manufacturing / production, use, reuse, maintenance, recycling and ultimate disposal of an object. During each of these phases of the product's life cycle, the product can have impacts on the environment as illustrated in Fig. 6. Life cycle analysis studies the environmental aspects and potential impacts throughout a product's life (i.e., cradle-to grave) from raw materials acquisition through production, use and disposal.[13]

Sharratt[12] states that a boundary can be drawn around the product life cycle. An (environmental balance(can then be created that considers the environmental impact of the manufacturing, use and disposal of the product, and the ability of the environment to accommodate these impacts. Reducing the process's environmental impact is an important consideration in improving the sustainability of a process. This systems approach provides a means of quantifying the tradeoffs that are being made in implementing an industrial process.

Processes contribute to direct (associated with this process) and indirect (associated with other parts of the lifecycle) effects which can be local, regional or global in scope. The general trend in life cycle analysis is not only to consider the direct impacts of pollution, but also the efficiency of resource utilization. The impact of the process thus depends not only on the amount of materials released into the environment, but also on its location, social acceptance, resource utilization and risk of accident.[12]

Currently, application of life-cycle assessment to a given process is difficult because of limited data availability, allocation of impacts between co-products, and difficulties defining the system.[14] Currently, there is limited reliable, publicly-available data for a variety of products, including electricity.[15] This limited data makes evaluating the net pollution reduction of a process change that changes the amount of electricity required difficult when the emissions from electrical generation are included. Indeed, there can be substantial differences in electricity life cycle data based on the electricity generating profile for the location of the metal finishing facility. A further complication of life-cycle assessment occurs when more than product is produced by a process. Allocation of impact between multiple products is not straight-forward. Rather allocation of impacts between the two products are typically based upon factors such as the relative mass or economic value of the products. These two problems highlight the need to be able to define what portions of the product's life cycle are part of the system for a meaningful analysis. Clearly, the need to consider aspects of the process beyond the control of the metal finishing facility can obfuscate the results of a life cycle assessment.

Waste Reduction (WAR) Algorithm

As an alternative, the life cycle assessment process can be pared down to focus on simply the manufacturing portion of the process. The US Environmental Protection Agency has developed the WAste Reduction (WAR) algorithm to evaluate the environmental friendliness of the manufacturing step in the life cycle analysis of a product. Young and Cabezas[16] generally define the potential environmental impact (PEI) of a given input or output stream as the effect that the material and energy contained in the stream would have on the environment if it was emitted to the environment. The PEI for the plating plant is given summing the PEIs of all streams using the equation:

$$\dot{I} = \sum_j \dot{I}_j = \sum_j \dot{M}j \sum_k x_{k,j} \, \Psi_k$$

where $\dot{M}$ is the mass flow rate of the stream j, $x_{k,j}$ is the concentration of component k in stream j and Ψ_k is the potential environmental impact for chemical k. This formulation of $\dot{I}$ does not consider possible synergistic effects between the chemicals in the streams.

Chemicals can impact the environment in various ways, including, but not limited to, human toxicity, global warming potential, ozone depletion potential and acid rain potential. The WAR algorithm allows a chemical to be scored for each of these potential environmental impact categories. In order to consider each risk category, the potential environmental impact (Ψ_k) for a chemical can be determined by summing the specific environmental impacts of chemical:

$$\Psi_k = \sum a_n \Psi^s_{k,n}$$

where:

a_n = is the weighting factor for impact category n and

$\Psi^s_{k,n}$ = the category n specific environmental impact for chemical k

The weighting factors enable the user to vary the importance of each risk category for the analysis being conducted. The categorical specific environmental impact for a chemical can be viewed as a ratio of the score of a chemical in the category to the average score of chemicals in that category. For example, the chemicals can be scored based on human toxicity using factors such as the LD50.

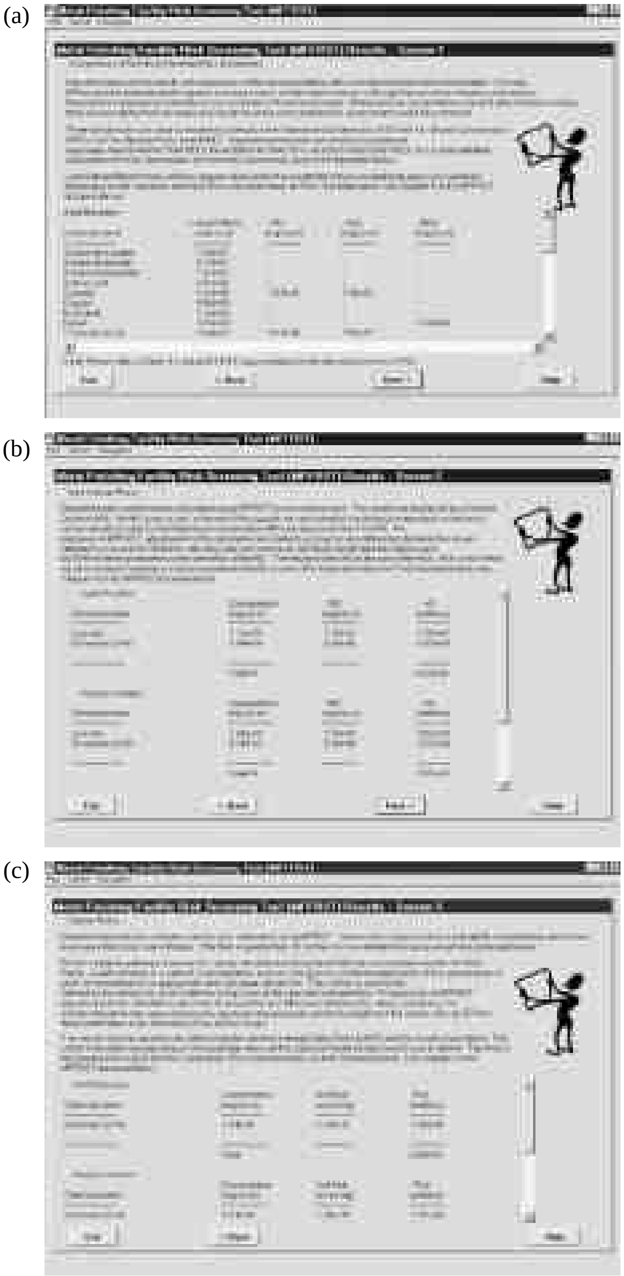

Fig. 5—Result screens from MFFRST.

Young, *et al.*[17] utilized WAR for a case study that investigated three processes for allyl chloride production. In the base case, allyl chloride was produced by combining propylene and chlorine in a reactor at 51°C (952°F) and 0.3 MPa (43.5 lb/in.^{2}), and significant quantities of hydrogen chloride, 2-chloropropene and 2,3 dichloropropene were produced. The product from the reactor was cooled using a series of heat exchangers to -50°C (-58°F), and approximately 80 percent of the HCl was flashed from the reactor products. The HCl was absorbed by water to produce 31.5 percent HCl. The remaining reaction mixture was distilled to separate the remaining HCl, 2-chloropropene and 2,3 dichloropropene from the allyl chloride. The first alternative case involved reducing the amount of refrigeration of the reaction products by increasing the pressure in the distillation towers. This modification required the addition of a compressor and allowed the elimination of a flash drum and distillation tower. The second alternative included changes made in the first alternative and improved the yield of

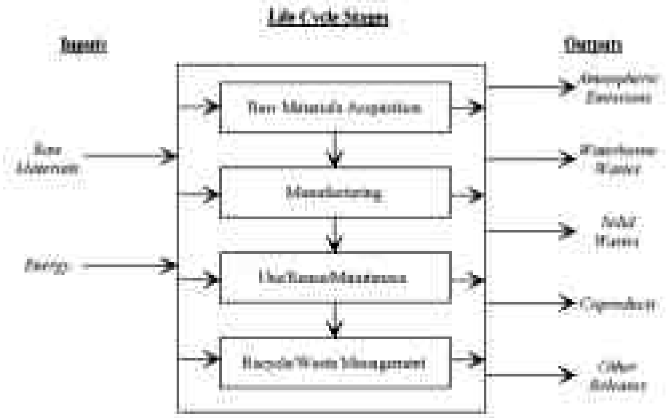

Fig. 6—Life cycle assessment stages and boundaries.[24]

allyl chloride in the reactor by reducing the reaction temperature to 470°C (878°F). The second design alternative was found to have the lower PEI and greater operating profit through a reduction in capital costs, reduction in energy costs, and improved allyl chloride yield.

Metal Finishing Waste Management & Pollution Prevention

The basic economic fact is that pollution prevention should not be an economic burden for any industry. Pollution prevention should provide industries both environmental and economic benefits. Most metal finishing plants do not have in-depth understanding of process principals, and do not know exactly how production and waste minimization are correlated. The reality is that plants currently over-consume chemicals, energy and water; and that waste generation is always more than it should be. The key to waste reduction is the control of production quality. The fundamental components of profitable pollution prevention are the process principals that explain how parts are rinsed, cleaned and plated, and how the waste is generated in various operations. These principals are nothing more than mass balances, energy balances, thermodynamics and chemical kinetics.

Lo and Tsao[18] conducted an economic analysis of waste minimization by surveying 35 electroplating facilities in Taiwan and found that the majority of shops used source reduction techniques for waste minimization. Although process flow sheets varied, it was obvious that drag-out and rinse waters were the major sources of waste and that rinses accounted for the most water use and were the largest generation of wastewater. Of the 35 plants reviewed, 30 practiced rinse water reduction, and 21 utilized drag-out minimization. Lo and Tsao[18] also conducted an economic analysis of three different pollution prevention schemes for a chromium and nickel plating facility. Of the three schemes evaluated, one scheme (still rinse after plating bath with rinse solution concentrated by reverse osmosis and returned to the plating bath) was profitable while two other schemes (electrolytic recovery with rinse water purified by ion exchange and reused; and still rinse followed by a two stage countercurrent rinse and electrolytic recovery of nickel from the rinsewater) were not.

Schwartz and McBride[19] conducted a survey of 458 metal plating shops located in Orange, Los Angeles, and Santa Clara counties in California to determine whether these shops were aware of waste reduction methods, whether the firm adopted or rejected the option, and what obstacles prevented firms from adopting additional waste reduction methods. The primary reasons for non-adoption of waste reductions techniques were economic, either high price or concern that non-complying shops would undercut prices, the technique would harm product quality or space limitations. Larger shops, those shops that spent more for waste disposal, were more likely to adopt hardware intensive waste reduction technologies. A significant number of shops indicated that organizational issues such as employees ignoring waste reduction techniques or employees who do not speak English well enough to communicate more than basic tasks, precluded adoption of waste reduction technologies.

In practice, rinse times are set conservatively to ensure proper rinsing because process dynamic behavior is not well known.[20] The process uncertainties not only limit the ability to increase process efficiency, but result in greater chemical and water usage through overcleaning and extended rinsing. Chemical concentrations greater than optimal may lead to increased operational costs resulting from greater sludge and wastewater generation. Most plating plants generate more sludge than necessary (avoidable sludge) as a result of improper use of chemicals, high flow rate of rinsewater, excessive dragout into rinse tanks and unnecessary dumping.[21]

Luo and Huang[22] indicate that an electroplating process is a typical chemical process where a number of process units are sequentially connected. Source reduction can be realized through process/equipment modification, process control, process optimization, technology change, material substitution and product reformulation. The authors state that waste streams generated by the process can be classified into four categories: wastewater, spent solvents, spent process solutions and sludge. Mathematical models are useful in solving waste management problems. Because of the complexity, non-linearity and uncertainty involved however, first-principal models are difficult to develop. Empirical models can be generated more readily, but because of the multi-dimensional and highly non-linear nature of waste management problems, sufficient data may never be available to develop a model of the process. For this reason, Luo and Huang chose a fuzzy logic approach to the waste management process. It utilizes basic chemical engineering principles and artificial intelligence, developing a personal computer-based waste management decision support system. They utilized the fuzzy logic approach in O2P2EP software, which is an intelligent decision making tool that utilizes fuzzy logic and knowledge engineering to tackle source-reduction problems in electroplating plants. It conducts a detailed process analysis of waste generation mechanisms, evaluates waste management practice, identifies waste management bottlenecks and prioritizes waste management strategies in terms of cost and technical efficiency.

Zhou, *et al*.[23] analyzed a switchable water allocation network (SWAN) to reduce the quantity of wastewater generated in a metal finishing plant. The SWAN analyzes the electroplating line by constructing a superstructure consisting of all possible connections among process units. The water use and reuse network (WURN) is determined to be the optimal steady-state rinsing superstructure. It is designed to maximize the reuse of used rinse water in different rinse steps. The SWAN then develops a second WURN based on the dynamics of the individual rinse tanks, restricting flow to the rinse tank once the water quality in the tank has reached acceptable concentrations. The authors indicate that typical practice in the electroplating industry is to continue introducing fresh water into a rinse tank following attainment of acceptable rinse water quality to ensure that the quality of water in the rinse is acceptable. Use of a dynamic rinsing model provides a secondary WURN or water allocation network (WAN) that requires less fresh water, and generates less wastewater than the original WURN. The authors assert that additional water savings can be realized through implementation of the WAN. The analysis of an electroplating line showed that the addition of four valves allowed the system's operational mode to be switched between the primary and secondary

WANs. Implementation of the SWAN would reduce annualized operating costs by 39 percent for the process evaluated.

Conclusions

The EPA has completed the first version of MFFRST, which provides risk screening for workers and individuals living around the metal screening facility. MFFRST can be obtained from EPA via the internet. MFFRST meets the goal of the 1997 Metal Finishing R&D plan for emission and risk characterization.

The 2000 update of the National Metal Finishing R&D Plan indicates a shift in the needs of the metal finishing industry from a risk screening tool to a tool that will aid the plating facility to identify cost-effective pollution prevention techniques. Historically, pollution prevention in the metal finishing industry work has focused mainly on end-of-pipe treatment technologies. As shown above, a variety of methods have been established to aid pollution prevention within the chemical process industry in general, and the metal finishing industry in particular. These pollution prevention tools are based on computer process models. The US EPA is currently preparing a follow-up computer-based pollution prevention tool that applies these methods to the metals finishing industry.

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