Design of an Optimal Reversed Drag-out Network for Maximum Chemical Recovery in Electroplating Systems

*by Qiang Xu and Yinlun Huang**

In electroplating lines, chemical losses from either cleaning units or plating units, through drag-out, to succeeding flow rinse units are a major economic and environmental concern, since the loss can dramatically increase the operating cost as well as the wastewater treatment cost. To alleviate this problem, a concept of reversed drag-out has been introduced. The main task for designing a reversed drag-out system is to redesign its rinse systems under the constraints of total cost, chemical recovery efficiency and parts rinse quality. In this paper, a simple, general and effective design and operation strategy development method is introduced for deriving an optimal REversed Drag-Out NEtwork (REDONE) system. The method is capable of providing comprehensive design and operation information so that designers can conveniently identify the most desirable design for chemical recovery in electroplating lines. A case study demonstrates the efficacy of the engineering design method.

Electroplating operations consume huge amounts of chemical solvents and plating solutions daily.[1-4] It is known that chemical losses from cleaning and plating steps can be as high as 60% and 30% of overall consumption, respectively, in normal production.[5] It is known that a major mechanism of chemical loss is drag-out, through which certain amounts of chemical-containing solutions are carried out from cleaning or plating units and then enter the succeeding flow rinse systems. The lost solutions are subsequently rinsed off by the rinse water and flow into wastewater treatment facilities. Significantly, the chemical loss not only dramatically increases operating costs for additional solvents, plating solutions and fresh water, but also requires extra effort for waste treatment, which is also costly. By all means, therefore, drag-out related chemical loss to wastewater must be minimized.[6-9]

Drag-out related chemical loss could be recovered, if the path of drag-out to wastewater is terminated. It is possible to let the chemical-containing solution dragged out from a cleaning or plating unit enter a static rinse system, rather than a flow rinse system. In this way, the amount of solution can be recovered if it is pumped back to the cleaning or plating unit. This is the fundamental idea of the reversed drag-out concept. The challenges for implementing the concept, however, are to design an economically and environmentally attractive reversed drag-out system at a lowest possible total annualized cost (TAC), and with maximum solution recovery and the best possible rinsing, cleaning and plating quality. Unfortunately, the practicing technologies are almost all experience-based, and thus the designs are usually far below optimum.[5,10] In reality, at present, reversed drag-out systems are very limited in their adoption.

General reversed drag-out design

Figure 1 depicts a conceptual design of a REversed Drag-Out NEtwork (REDONE), based on the reversed drag-out concept. The design contains a master unit (either a plating unit or a cleaning system that may have more than one

Nuts & Bolts: What This Paper Means to You

Drag-out losses comprise a major cost in plating operations, both from economic and environmental standpoints. This paper develops that means for optimizing a reverse drag-out scheme, which promise to reduce considerably material losses while reducing environmental consequences. Behind the math is an engineering solution for many such problems.

* *Corresponding Author:*
Prof. Yinlun Huang
Department of Chemical Engineering and Materials Science
Wayne State University
Detroit, MI 48202
Phone: 313-577-3771
Fax: 313-577-3810
E-mail: yhuang@wayne.edu

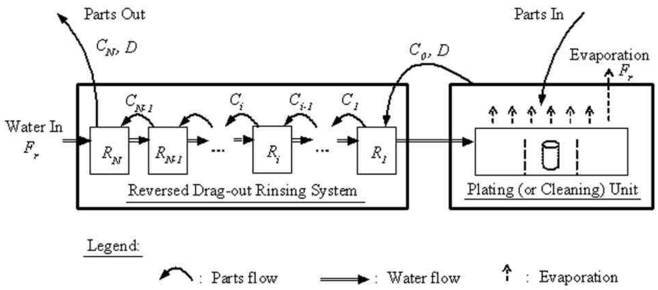

Figure 1—Schematic diagram of an integrated reversed drag-out rinsing system.

cleaning unit), and a number of static rinse units lined in series. In operation, each barrel or rack of workpieces, after finishing an operation in the master unit, enters the rinse units one by one for rinsing the solution dragged out from the master unit. The collected lost solution in the static rinse system is subsequently pumped back to the master unit. Thus, when the parts leave the last rinse unit, the chemicals dragged out with the barrel or rack can reach a minimum.

As shown, freshwater is periodically fed into rinse unit R_N, and the solution-containing rinse water in R_N flows to R_{N-1}, ··· and R_1 periodically. Finally, the solution-containing rinse water in R_1 is periodically pumped into the master unit. The solution temperature of the master unit is usually higher than the ambient temperature. For operational reasons, the unit may have forced evaporation, causing continuous evaporation of water from it. Thus, the rinse water flow from rinse unit R_1 to the master unit should compensate the evaporation loss.

The main design and operation tasks of a REDONE system can be (1) a system configuration (*i.e.*, the number of static rinse units or the number of rinse stages) and (2) operational settings, such as freshwater flow rate, total processing time and drag-out rate. In order to help develop an optimal system, a general, fundamentally-based system modeling is introduced below.

Steady-state system modeling

As shown in Fig. 1, the material balance of a rinse unit in the system can be derived below:

$$DC_i + F_r TC_i = DC_{i-1} + F_r TC_{i+1}, \qquad i = 1, 2, \ldots, N-1 \quad (1)$$

$$DC_N + F_r T C_N = DC_{N-1} \quad (2)$$

where

C_i = the chemical concentration of the i^th static rinse unit,
D = the amount of drag-in or drag-out,
F_r = the flow rate of freshwater entering the N^th static rinse unit,
N = the total number of static rinse units in the REDONE and
T = the total processing time of a barrel or rack of parts in the electroplating line.

The freshwater flow rate F_r must equal the reversed drag-out flow rate of each rinse unit in order to maintain a steady-state operation. Solving equations (1) and (2) gives,

$$\frac{C_i}{C_{i-1}} = \frac{1}{1 + \frac{F_r T}{D} - \frac{F_r T}{D}\frac{C_{i+1}}{C_i}} \quad (3)$$

$$\frac{C_N}{C_{N-1}} = \frac{1}{1 + \frac{F_r T}{D}} \quad (4)$$

By defining the following two parameters,

$$p_{i,i-1} = \frac{C_i}{C_{i-1}} \quad (5)$$

$$\alpha = \frac{F_r T}{D} \quad (6)$$

Equations (3) and (4) can be rewritten, respectively, as,

$$p_{i,i-1} = \frac{1}{1 + \alpha - \alpha p_{i+1,i}} \quad (7)$$

$$p_{N,N-1} = \frac{1}{1+\alpha} \quad (8)$$

where $p_{i,i-1}$ is the concentration ratio of the drag-out to the drag-in for rinse unit R_i. The parameter α is the ratio of the recovery rate to the drag-out rate. The flow rate F_r must be equal to the evaporation rate of the master unit. Thus, α is also the ratio of the evaporation rate to the drag-out rate.

According to equations (1) and (2), for a given REDONE, after α and C_0 are determined, the chemical concentrations, C_i, $i = 1, 2, \cdots, N$, in the rinse units can all be calculated. These concentrations are the indicators of chemical recovery by the REDONE. In this regard, the following parameter needs to be introduced.

$$P_i = \prod_{j=1}^{i} p_{j,j-1} = \frac{C_1}{C_0}\cdot\frac{C_2}{C_1}\cdot\ldots\cdot\frac{C_i}{C_{i-1}} = \frac{C_i}{C_0} \quad (9)$$

The parameter, P_i, namely the rinse effectiveness ratio, provides a simple way to calculate the chemical recovery effectiveness in the REDONE. In reality, the number of rinse stages in a REDONE is no greater than three. The following lists the expressions of the rinse effectiveness ratio for the REDONE's with a one-stage, two-stage or three-stage rinse.

$$P_1 = \frac{C_1}{C_0} = \frac{1}{1+\alpha} \quad (10)$$

$$P_2 = \frac{C_2}{C_0} = \frac{1}{1+\alpha}\cdot\frac{1}{1+\alpha-\alpha\frac{1}{1+\alpha}} \quad (11)$$

$$P_3 = \frac{C_3}{C_0} = \frac{1}{1+\alpha}\cdot\frac{1}{1+\alpha-\alpha\frac{1}{1+\alpha}}\cdot\frac{1}{1+\alpha-\alpha\frac{1}{1+\alpha-\alpha\frac{1}{1+\alpha}}} \quad (12)$$

These expressions show that the P_i values are the function of α only. In order to design an effective REDONE, α often needs to be identified when the rinse effectiveness (P_i) is given. According to equation (10) through (12), the following relationships are identified:

$$\alpha = \begin{cases} \frac{1}{P_1} - 1; & \text{for one - stage rinse} \\ -\frac{1}{2} + \sqrt{\frac{1}{P_2} - \frac{3}{4}}; & \text{for two - stage rinse} \\ \frac{1}{6P_3}\sqrt[3]{\theta} - \frac{4P_3}{3\sqrt[3]{\theta}} - \frac{1}{3}; & \text{for three - stage rinse} \end{cases} \quad (13)$$

where

$$\theta = \left(-80P_3 + 108 + 12\sqrt{3\left(16P_3^2 - 40P_3 + 27\right)}\right)P_3^2 \quad (14)$$

By using equation (9), a new parameter, R_N, the chemical recovery index, is introduced below.

$$R_N = \left(1 - P_N\right) \times 100\% \quad (15)$$

The model above is valid under the following assumptions:

- perfect mixing in the rinse tanks,
- equilibrium conditions,
- the use of rinse water containing very low impurities and
- no other significant build-up of impurities (such as brightener breakdown products in the case of a nickel plating bath).

Model-based system analysis

The equations above are so simple that one can use them readily to evaluate the chemical recovery effectiveness and to determine the number of static rinse stages necessary in a REDONE. As an illustration, the models in equations (6), (10) through (12) and (15) are used to simulate three REDONE designs:

- Design A (with one rinse unit and one master unit),
- Design B (with two rinse units and one master unit) and
- Design C (with three rinse units and one master unit).

Figure 2 provides the rinse effectiveness ratio (P_N) and the chemical recovery index (R_N) for each design. As shown in Fig. 2(a), the three P_N values are all decreased when parameter α is increased (*i.e.*, either the freshwater flow rate or total processing time increases, or the drag-out decreases). When α reaches 10, the P_N value will be 0.091, 0.009 and 0.0009 for Designs A, B and C, respectively. These indicate the best rinse quality that each design could obtain. Figure 2(b) also shows the chemical recovery rates as a function of α. As the α value approaches 10, the chemical recovery can reach 90.9%, 99.1% and 99.91% for Designs A, B and C, respectively.

The information revealed in Fig. 2 is valuable for the design and operation of a REDONE. From the design point of view, after a P_N value is selected (*e.g.*, 0.1, which means 90% of the chemical residue on the parts surface needs to be washed out), the three designs can be evaluated with the assistance of equations (13) and (14) (see Points A (9.00, 0.1), B (2.54, 0.1) and C(1.66, 0.1), where the first and the second numbers in the parentheses are the values

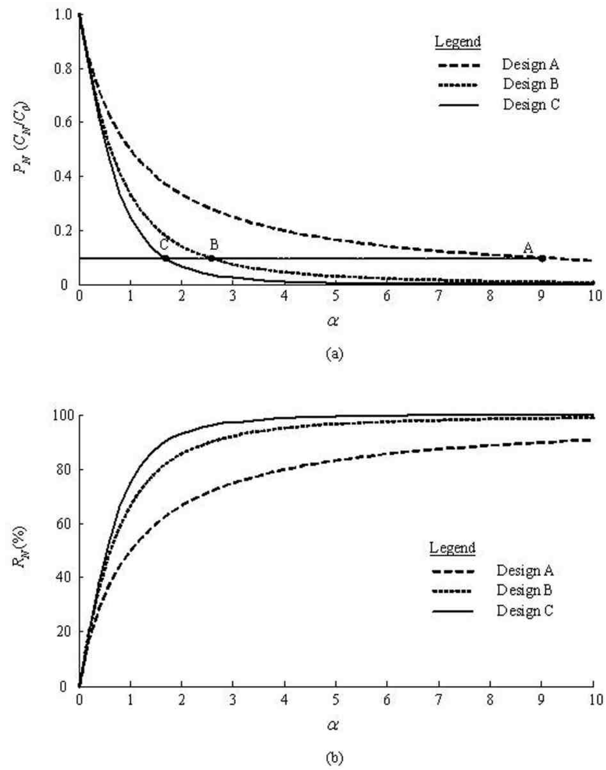

Figure 2—Comparison of rinse efforts under three REDONE designs: (a) rinse effectiveness ratio vs. α and (b) chemical recovery index vs. α.

of α and P_N, respectively). According to equation (6), parameter α is a function of F_r, T and D, which are all parameters related to design and operation. Thus, α can be used as a key parameter to develop a cost function for economic analysis and the selection of design alternatives.

Cost estimation

Essentially, the cost estimate of a REDONE is made for the static rinse units as well as for the necessary facilities for evaporation and ventilation with the master unit. Additional costs may include those for energy and labor. A determination of total annualized cost (TAC) requires engineering knowledge related to the number of units, rinse capacity, pollutant loading level, water flow rate, and the like. If α is mainly dependent on the flow rate F_r and the emission handling facilities are already in place, then the cost functions for equipment purchase (C_{eq}), equipment installment (C_{in}), and operation (C_{op}) can be generally expressed as follows:

$$C_{eq} = a_1 \alpha^g + a_2(N) \quad (16)$$

$$C_{in} = a_3 C_{eq} \quad (17)$$

$$C_{op} = a_4 \alpha^g \quad (18)$$

where α is already defined in equation (6), g is a real number and α_i is a cost coefficient. Based on the above cost equations, a general TAC function is suggested below:

$$TAC = a\alpha^g + b(N) \quad (19)$$

where a and $b(N)$ are, respectively, non-rinse-stage related and rinse-stage related parameters. These parameters can be determined in accordance with specific applications. Parameter α is related to many factors, such as water and energy consumption, wastewater treatment, heating or ventilation. Defining an exact form of TAC is usually very difficult. In the simplified form shown in equation (19), the TAC is a monotonically increasing function with respect to α. This means that if the freshwater flow rate or the total processing time for parts is increased, or the drag-out flow rate is decreased, then TAC will be increased.

Design and operation strategy development algorithm

The model-based system analysis method and the cost function can be used to design an optimal REDONE system and determine the most desirable operation strategy for the system. A simple and general design/operation algorithm is described below.

Step 1. Determine the number of candidate designs (*i.e.*, the number of static rinse stages, *N*).

Step 2. Generate a P_N vs. α plot [as in Fig. 2(a)] using equation (9), or more specifically equation (10), (11) or (12), and/or an R_N vs. α plot [as in Fig. 2(b)] using equation (15) for each design candidate.

Step 3. Generate a TAC vs. α plot for each design candidate using equation (19).

Step 4. Select a rinse quality requirement (*i.e.*, a P_N value) or a chemical recovery expectation (*i.e.*, a R_N value).

Step 5. Identify an α value from Fig. 2 (or more specifically, using equations (13) and (14)) for each design candidate.

Step 6. Use the TAC vs. α plot to determine the cost for each design candidate.

Step 7. Select the most desirable system (*i.e.*, the number of static rinse stages) based on the TAC.

Step 8. For the selected system and the calculated α value, determine the values of the operational parameters F_r, *T* and *D*.

Application

The above design and operation strategy development algorithm has been used successfully to derive optimal REDONE systems. As an illustration, a plating solution recovery problem is demonstrated here. The master unit for the REDONE is an electroplating unit. The design task is to determine the number of static rinse units and the corresponding freshwater flow rate F_r.

In this case, the production rate is 6.0 barrels/hr, *i.e.*, the product processing cycle time, *T*, is 10 min. and the drag-in or drag-out rate, *D*, is 2.0 L/barrel (0.53 gal/barrel). The freshwater flow rate F_r is equivalent to the chemical solution recovery rate from rinse unit R_1 to the master unit, and it is also equal to the evaporation rate in the master unit (as in Fig. 1). According to Cushnie,[5] if a plating solution is operated at 27°C (80°F), and the equipment is an atmospheric evaporator with an evaporative capacity between 12.1 and 114 L/hr (3.2 and 30 gal/hr), then α could vary in the range of 1.0 to 9.3.

As stated previously, generating a precise form of the TAC function is difficult and quite often it is a case-by-case problem. In this work, our main focus is to demonstrate a methodological advantage of the proposed REDONE, and a relatively simple form of TAC is used in this example. Three design alternatives [*i.e.*, Design A (one-stage rinse), Design B (two-stage rinse) and Design C (three-stage rinse)] are to be evaluated using the following cost function.

$$TAC = \begin{cases} 4600\alpha + 4000, & N = 1 \\ 4600\alpha + 8000, & N = 2 \\ 4600\alpha + 14000, & N = 3 \end{cases} \quad (20)$$

By using equations (10) through (12), the P_N and α relationship for each design is plotted in Fig. 3(a). By using equation (20), a plot of TAC vs. α is generated in Fig. 3(b), where the three curves are for the three design alternatives.

The rinse quality considers three standards to investigate, *i.e.*, (1) $P_N \le 0.10$, (2) $P_N \le 0.07$ and (3) $P_N \le 0.03$. For each of the three rinse standards, an α value for each design can be identified in Fig. 3(a). It should be noted that more accurate values could be obtained with equations (13) and (14). These α values are used to determine the TAC's. Table 1 summarizes the solution evaluation results. For Design A, if the rinse requirement is too high (*i.e.*, $P_N \le 0.07$), then the α value will be beyond the pre-identified range of 1.0 to 9.3. The design with these rinse standards will not be feasible and thus the relevant entries in Table 1 contain no information.

Figure 3 shows that for $P_N \le 0.10$, α(A), α(B) and α(C) are equal to 9.00, 2.54 and 1.66, respectively. With the identified α values, the TAC for each design can be determined from Fig. 3(b). That is, TAC[α(A)], TAC[α(B)] and TAC[α(C)] are $45,400, $19,684 and $21,636, respectively. Correspondingly, the freshwater flow rate, F_r, for Designs A, B and C, are 1.8, 0.508 and 0.332 L/min (0.48, 0.13 and 0.09 gal/min), respectively.

The same approach can be used to determine the design and operation of each REDONE system under different rinse quality requirements or chemical recovery expectations. Table 1 shows that if the rinse quality requirements are set to 0.10, 0.07 and 0.03, or the chemical recovery is set to 90%, 93% and 97%, then the optimal REDONE systems will be, respectively, Designs B (two-stage rinse), B (two-stage rinse) and C (three-stage rinse), and the optimal freshwater flow rates, F_r, are 0.508, 0.636 and 0.558 L/min (0.13, 0.17 and 0.15 gal/min), respectively.

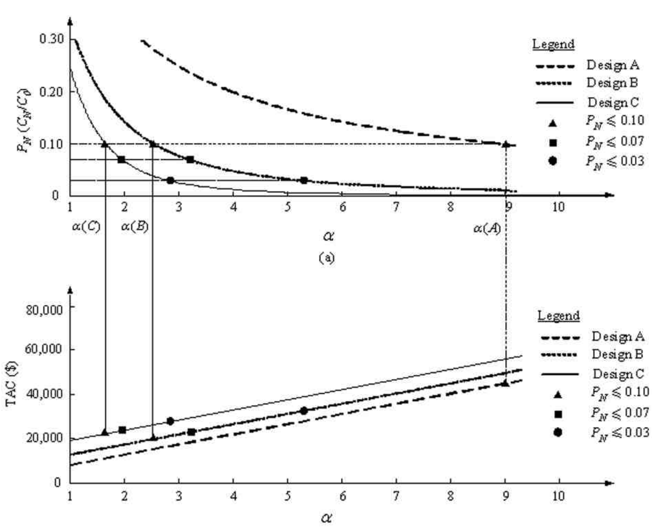

Figure 3—Solution representation with the fast assessment method: (a) rinse effectiveness ratio vs. α and (b) total annual cost vs. α.

Table 1
Solution evaluation and comparison

Rinse Requirement (P_N)	Chemical Recovery (R_N)	Design A (w/ one-stage rinse)			Design B (w/ two-stage rinse)			Design C (w/ three-stage rinse)		
		α	F_r (L/min)	TAC ($)	α	F_r (L/min)	TAC ($)	α	F_r (L/min)	TAC ($)
≤ 0.10	≥ 90%	9.00	1.8	45,400	2.54	0.508	19,684	1.66	0.332	21,636
≤ 0.07	≥ 93%	–	–	–	3.18	0.636	22,628	1.96	0.392	23,016
≤ 0.03	≥ 97%	–	–	–	5.21	1.042	31,966	2.79	0.558	26,834

It should be noted that the REDONE design could reach a very high rinse quality [*e.g.*, Design C in Fig. 3(a)]. Thus, in general, there will be no need for a flow rinse after the REDONE. But in some special cases (*e.g.*, when the build-up of impurities cannot be effectively avoided), a flow rinse may be considered after the REDONE.

Concluding remarks

Tremendous losses of chemicals from chemical cleaning and electroplating units in electroplating systems have been a major concern in the electroplating industry. These losses have led to significant increases in both operating and waste treatment costs. Industrial solutions to the chemical loss reduction are basically heuristic-based, and thus the effectiveness of chemical recovery is very limited. The model-based design and operation strategy development method presented in this paper provides the industry with a simple, general and effective method for deriving an economically and environmentally optimal REversed Drag-Out NEtwork (REDONE) system. Such systems can be used to recover chemical losses from cleaning systems and plating systems in electroplating lines with any design capacity.

Acknowledgement

This work was in part supported by National Science Foundation (CTS 0091398 and DMI 0225843) and the Institute of Manufacturing Research at Wayne State University.

References

1. P. Gallerani, *Plating & Surface Finishing*, **83**, 48 (January 1996).
2. L.J. Durney, *Electroplating Engineering Handbook, 4th Ed.*, Van Nostrand Reinhold, New York, NY, 1984.
3. M.F. Dahab, D.L. Montag & J.M. Parr, *Water Science & Technology*, **30** (5), 243 (1994).
4. U.S. Environmental Protection Agency, *National Metal Finishing Strategic Goals Program: An Industry's Voluntary Commitment to a Cleaner Environment, EPA 231-F-99-002, OPR/ISPD*, EPA, Washington, DC, 1999.
5. G.C. Cushnie, *Pollution Prevention and Control Technology for Plating Operations*; National Center for Manufacturing Sciences, Ann Arbor, MI, 1994.
6. H.R. Lou & Y.L. Huang, "Qualitative and Quantitative Analysis for Environmentally Benign Electroplating Operations, Chapter 5," in *Green Engineering*, P.T. Anastas, L.G. Heine & T.C. Williamson, Eds., Oxford Press, New York, NY, 2001.
7. H.R. Lou & Y.L. Huang, *Plating & Surface Finishing*, **87**, 59 (November 2000).
8. Y.H. Yang, H.R. Lou & Y.L. Huang, *Plating & Surface Finishing*, **86**, 80 (April 1999).
9. Y.H. Yang, H.R. Lou, and Y.L. Huang, *Waste Management*, **20**, 311 (2000).
10. K.Q. Luo, and Y.L. Huang, *Int'l. J. Eng. App. of Artificial Intelligence*, **10**, 321 (April 1997).

About the Authors

Qiang Xu is a research associate in the Department of Chemical Engineering and Materials Science at Wayne State University. He holds B.S., M.S. and Ph.D. degrees from Tsinghua University, China, all in chemical engineering. He also holds a B.S. degree from Tsinghua University in environmental engineering. His research interests include process modeling, scheduling, dynamic simulation and optimization, industrial process pollution prevention and waste minimization and chemical process flexibility analysis.

Yinlun Huang is Professor of Chemical Engineering and Materials Science at Wayne State University, Detroit, MI. He received his BS from Zhejiang University, China, and M.S. and Ph.D. from Kansas State University, all in Chemical Engineering. His research interests include process design and synthesis, process modeling and control, process simulation and optimization, process pollution prevention, information processing and decision making, computational biology, and sustainable engineering. His research has been supported by NSF, EPA, AESF and various industries, and he has published extensively in all these areas. Dr. Huang is currently serving on the AESF Board of Directors.