Cross-Media Transfers of Hazardous Wastes

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Introduction

The current issues of landfill bans, groundwater contamination, waste-end taxes and source reduction of hazardous wastes have rekindled interest in a systems view of environmental management. While this recent interest is new, the basic concept is not. The physical Law of Conservation of Mass as embodied in materials or mass balance has underlain most residuals management research (e.g. Ayres and Kneese [1969]; Kneese and Bower [1979]). As society grapples with the complex problem of toxic and hazardous chemical residues and their distribution in the environment, mass balance is receiving renewed attention in the form of cross-media transfers. The focus of this renewed interest is the movement and transformation of residuals among environmental media (soil, air and water) after discharge. Our early public lessons in applied ecology taught us that the environment is a single integrated system and that there are frequently unintended consequences associated with the human use of that environment. The contemporary lessons from the identification and cleanup of uncontrolled hazardous waste sites under the "Superfund" program lends a new impetus to our reconsideration of these concepts.

Cross-media transfers of pollutants are generally differentiated on the basis of causation. Some authors (Lowe, Lewis and Atkins [1982]) reserve the transfer designation for those migrations of residuals among media that are the result of natural processes such as precipitation, leaching, or sedimentation. Clearly, the heated policy debate surrounding the land disposal of hazardous and toxic wastes focuses on the possibilities of cross-media transfers from land to groundwater through the natural process of leaching. However, not all such inter-media movements are the result of natural forces; some consciously result from environmental policy decisions. For example, water quality standards usually result in the disposal of water treatment by-products that previously would have been discharged directly to watercourses. It is estimated that pollution controls have resulted in the production of 118 million dry metric tons of sludge annually (Conservation Foundation [1984]). Such policy-induced changes in residuals distribution are sometimes differentiated as cross-media trade-offs. While movements of residuals among media are commonplace manifestations of the interconnectedness of our natural environment, those stimulated by deliberate policy are not. We focus our attention in this paper on the latter source of transfers.

The paper is organized into roughly two major sections. The first presents a brief overview of the current institutional and legislative framework. The second presents an empirical illustration of these concepts through a process analysis of an electroplating firm. Finally, the results of the empirical analysis are synthesized into their implications for contemporary environmental policy.

The Institutional Setting

The vehicle chosen to illustrate the precise nature of the cross-media problem and its consequences is the occasion of the impending imposition of pretreatment standards under the Clean Water Act of 1977. Of particular interest is the metal finishing industry which has been described by the Environmental Protection Agency (EPA) as that sector likely to suffer the greatest economic hardship from the

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implementation of these regulations (EPA [1977]).

The primary focus of pollution control legislation with respect to the metal finishing industry has been the regulation of wastewater constituents and the amounts discharged. The Federal Water Pollution Control Act Amendments of 1972 (PL 92-500) established a comprehensive program to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters." The reauthorization of this program in the form of the Clean Water Act of 1977 (PL 95-217) incorporated provisions requiring EPA to establish a series of pretreatment standards designed to curtail the discharge of toxic chemical wastes into publicly owned treatment works (POTW's) since these facilities are not generally designed to manage these effluents. Further, sufficiently high concentrations of these discharges reduce the effectiveness of such plants and limit the options for sludge disposal. Pretreatment standards for existing sources (PSES) and pretreatment standards for new sources (PSNS) were to be developed for 21 major industries including electroplating. The intent was to implement these regulations between April and July of this year. However, the Clean Water Act has technically expired, operating under continuing resolution for the past two years, and current Congressional action seems likely to change this timetable. The House of Representatives passed the Water Quality Renewal Act of 1984 on June 26th. This proposed legislation contains provisions which extends to 42 months the time industries have to comply with new standards for treating toxic wastes. The Senate's version contains a proposed amendment which would relax pretreatment standards.

For the electroplating industry, one result of compliance with pretreatment limitations will be the generation of significant quantities of sludge from on-site wastewater treatment prior to discharge. The heavy metals, cyanides and other toxic chemicals contained in these sludges cause these as well as other electroplating wastes to fall under the regulatory purview of the Resources Conservation and Recovery Act of 1976 (PL 94-580 or RCRA). RCRA's goal is the regulation of the "treatment, storage, transportation, and disposal of hazardous wastes which have adverse effects on health and the environment." RCRA is also currently up for reauthorization. At least one version, S-757, has provisions for the prohibition of the land burial of certain "ultrahazardous wastes" which include sludges contaminated with heavy metals (Exposure [1984]).

The final piece of relevant legislation is the Comprehensive Environmental Response, Compensation and Liability Act of 1980 (PL 96-510 or CERCLA) which was designed to establish a mechanism to clean up closed and abandoned waste sites and to establish joint liability for generators, transporters and disposers. A $1.6 billion "Superfund" was created to fund clean-up activities. Current proposals to amend CERCLA (scheduled for renewal in September of 1985) include an expansion of the size and duration of the "Superfund" through initiation of a waste end tax. In generic terms, a waste end tax is a fee levied on the generation, management (including transport, storage and treatment) and disposal of hazardous wastes.

In summary, the institutional setting in which the electroplating industry operates is complex, dynamic and characterized by direct regulatory management of environmental media. Further, it provides an immediate, real example of the cross-media problem. Electroplaters are faced with pretreatment regulations in the form of discharge concentration limits which may require the use of wastewater treatment technologies. The by-products of these operations will be sludges which are defined as hazardous wastes under RCRA. These pollution control residuals must be managed at a further cost to the generator. In addition, the liability rules established under CERCLA create the possibility of future costs. Each of the alternative disposal media, water or land, is managed separately rather than jointly.

In theory, a joint cost function could be estimated that would generate the total (and marginal) costs from any set of pollution discharge activities. With this function, policy makers could develop the optimal environmental control measures for each type of pollutant. (This assumes that the regulatory agency has knowledge of the firms' treatment cost functions.) In practice, however, environmental policy is developed in a piecemeal fashion with different groups within a regulatory agency, or even different agencies altogether responsible for making policy for each type of pollutant. Policies chosen through an optimization process over each pollutant separately will probably be sub-

optimal. The correct procedure is to optimize over both policies simultaneously. Lave [1984] has recently illustrated this with reference to the automobile industry. The present purpose is to examine some of the interactions which may result when policies seeking to regulate two different waste forms are followed. The results of the research reported here show that unexpected and possibly undesirable consequences may result which subvert the intent of either or both sets of pollution policies.

Process Analysis

A process analysis model of a copper-nickel-chromium electroplating line for a small job shop was developed in a mixed integer programming setting. Job shops are firms which electroplate as a service to other firms. Because their workload is in large part exogenously set, cost minimization was assumed as the firm's objective. Extensive research in waste reduction techniques for electroplating operations exists (see Metcalf, Willis and Dudek [1984] for references). Waste reduction can be accomplished through abatement, minimization, reuse or recycling. Abatement encompasses the range of production process and chemical substitutions while minimization includes the set of activities known as good housekeeping as well as activities which reduce the volume of the hazardous waste. Reuse implies very minor modification of the waste stream leading to input reclamation whereas recycling is reclamation through the application of recovery technologies. Five options were considered in this analysis—one waste minimization option (vacuum filtration), two waste abatement techniques (a "Providence" style rinse system and a closed counter-current rinse system) and lastly two recycling alternatives (reverse osmosis and evaporation). These options were chosen because of their wide applicability within the industry. The firm's optimization problem then is to:

$$\begin{aligned} \text{Min} \quad & C'X \\ \text{s.t.} \quad & AX \leq 0 \\ & P = Po \\ & K = \text{integer} \\ & X \geq 0 \end{aligned}$$

where X is the vector describing electroplating activities, A is the matrix of constraint coefficients, C is a vector of costs, Po is the exogenously given demand for plating services and K is a subset of X. The overall production process can be broken down into three general steps: surface preparation, electroplating, and post-electroplating treatment. Surface preparation includes cleaning, descaling or degreasing to provide a surface suitable for electroplating. Plating of the workpiece is next, followed by rinsing to remove excess plating solution.

After rinsing, the workpiece receives additional post-plating treatment. Residuals are created at all three steps of the process. However, to simplify the analysis, only those residuals created by the plating and rinsing process were tracked. This is reasonable since the vast bulk of residuals generated by this manufacturing process originate in these processes. Figure 1 presents a stylized tableau of the process analysis model which is described in greater detail in Metcalf, Willis, and Dudek [1984]. The first constraint set simply states that the workpiece must be rinsed by one of the three alternative rinse systems. These are the waste abatement technologies considered within the model. The three systems differ primarily in their efficiency of water use. More efficient rinse systems produce less wastewater requiring treatment. However, residuals concentration levels are higher. The choice of rinse system is critical since approximately 90% of the firm's wastewater can be generated by the rinsing process (Marks et al. [1979]).

Contaminated rinse water may either be treated, with metal constituents recovered for reuse in the plating process, or reduced in bulk through sludge dewatering techniques (constraint set 2). The third row of Figure 1 accounts for metallic inputs. Metals used for plating must either be purchased or obtained from recycling activities. Similarly, all the water used for plating and rinsing must be either fresh or recycled (row 4). Constraint sets 5 and 6 relate waste recycling and minimization activities to sludge and wastewater production while sets 7 and 8 track the residual metals. The process can be modeled assuming different levels of waste reduction. In particular, overflow from the vacuum filter (the liquid remaining after sludge generation through compaction) can be subjected to further treatment. While the results presented in this paper do not analyze that possibility, interested readers may find solutions from models incorporating these features in Metcalf,

Figure 1. Generalized Tableau*

		Plating	Rinse	Metals	Fresh Water	Recycling	Source Reduction	Sludge Disposal	Wastewater Disposal	Metals in Sludge	Metals in Wastewater	Capital	Pretreatment Standards	Right-Hand Side
Plating Line	(1)	$-I$	e											$= 0$
Water Treatment	(2)		$-I$			e	e							$= 0$
Metals	(3)	m_1		$-I$		$-m_2$								$= 0$
Fresh Water	(4)	f_1	f_2		$-I$	$-f_3$								$= 0$
Sludge Disposal	(5)					s_1	s_2	$-I$						$= 0$
Wastewater Disposal	(6)					w_1	w_2		$-I$					$= 0$
Sludge Residuals	(7)					q_1	q_2			$-I$				$= 0$
Wastewater Residuals	(8)					r_1	r_2				$-I$			$= 0$
Capital Acquisition	(9)		k_1			k_2	k_3					$-k_4$		$= 0$
Pretreatment Standards	(10)									g_1		g_2	$-g_3$	$\leq b$

* I denotes identity matrix
e denotes matrix of ones

Willis and Dudek [1984]. Constraint set 9 requires the firm to allocate capital to purchase waste recycling or minimization equipment in order to implement these procedures. This constraint set also captures scale effects across recycling technologies. The last row imposes the Clean Water Act's pretreatment standards on the job shop.

The full model contains 115 constraints and 109 variables, 13 of which are integer. The model was run on a CDC Cyber 175 computer using the MPOS branch and bound mixed integer algorithm. Typical running times for each problem were 2.5 seconds. Parametric mixed integer programming techniques based on principles set out by Geoffrion and Nauss [1977] were employed to carry out sensitivity analyses to test the robustness of the results and to model a variety of policy scenarios. Selected results are presented below.

Empirical Results

In order to establish a reference point against which firm response to policy could be compared, a "base case" scenario was modeled. This scenario represents the firm's cost minimizing choice of production techniques and input utilization in the absence of pretreatment standards or hazardous waste disposal taxes. The base solution does not necessarily represent the production or treatment processes currently employed by electroplating firms since decision makers are already responding to changing relative input prices and existing or anticipated government policies. However, the comparison of an unregulated solution with those constrained by alternative environmental policies allows the identification of activity changes stemming from policy influences. For example, if the solutions to both the base model and the model with pretreatment regulations indicate that a particular recycling option should be used, then it can be assumed that the unit should be employed currently to minimize cost rather than to attain environmental objectives. Obviously, this interpretation assumes unrestricted access to capital.

The results of the analysis are presented in a series of tables. Each provides information on the amount of fresh water consumed in the production process, the amount of wastewater and sludge to be discharged and the amount of wastewater that results from indirect dilution (wastewater produced from the less efficient series rinse systems). Also, the percentage of residual metals discharged in the wastewater (as opposed to those contained in sludges) and their concentrations are noted. Finally, the total metals discharged in wastewater are listed.

Electroplating pretreatment regulations differentiate platers on the basis of the quantity of effluent discharged. Small shops have a daily discharge of less than 38,000 liters (approximately 10,000 gallons) and are subject to effluent limitations on cyanide (chlorine amenable,) lead, cadmium and toxic organics. For the small copper-nickel-chromium plater modeled in this analysis, the imposition of PSES limits as defined for small dischargers did not change the optimal mix of activities. Subsequently, the effects of imposing the large

plater standards were assessed. In this model, effluent limitations on copper, nickel, chromium and total metals were in effect. To simplify the analysis, residuals tracking was focused on nickel and chromium only. Copper and total metals can be considered to act as a surrogate in the model for the various pollutants that are created in the production process but not regulated by the Clean Water Act. The pretreatment standards imposed within the model are the 30 day average limits, the most stringent of the pretreatment requirements. The one day average limits are higher to accommodate occasional minor "slug" loads (batch or accidental discharges, equipment malfunctions, etc.). The 30 day limits for nickel and chromium are 1.8 and 2.5 milligrams per day respectively.

Table 1 presents selected results from the base and large plater regulation solutions with a constant marginal cost for sludge disposal. The results reveal a potential problem with these concentration-based standards. The concentration of residual metals in the wastewater falls below the limits set by the PSES once the standards are imposed. However, compliance has been attained in a way that subverts the intent of the legislation. The Clean Water Act specifically forbids the direct dilution of waste streams with fresh water to attain compliance. However, the older, water intensive series rinse systems, when utilized on the copper plating lines, produce effluent within the pretreatment limits as a natural consequence of their inherent inefficiency. Nearly two-thirds of the wastewater discharged under pretreatment standards results from indirect dilution caused by the retention of this older rinse technology. (More precisely, indirect dilution is defined as the difference between the amount of wastewater produced with pretreatment required and wastewater produced in the absence of pretreatment standards.)

Table 1. Pretreatment Results

	No Pretreatment Required	Pretreatment Required
Cost*	$168.04	$197.70
Water Consumption (liters/1040 m2)	2196	4323
Wastewater Production (liters/1040 m2)	1936	3953
Sludge Production (liters/1040 m2)	10.6	120.2
Indirect Dilution (liters/1040 m2)	0	2017
Percentage of Nickel and Chromium in Wastewater	40.5	15.0
Concentrations (mg/liter)		
Nickel	8.12	1.47
Chromium	2.63	0.48
Total Nickel and Chromuim in wastewater (grams)	21.24	7.71

* Included are variable costs plus pro-rated, annualized capital costs of purchasing recycling and source reduction equipment for a plating throughput of 1040 square meters.

As would be expected under pretreatment regulations, sludge production increases significantly. Even with indirect dilution, the percentage of metals discharged into the environment via wastewater has dropped to 15% from 40.5%. Thus, pretreatment standards result in the cross-media transfer of approximately 25% of the total residual metals load to land disposal. Compliance with the standards has added 17.7% to the firm's total costs. Under each of these scenarios, the effect of a waste end tax policy in the form of a per liter charge on sludge disposal was evaluated. This particular policy option is intended to stimulate waste reduction and reduce the demand for the landfilling of hazardous wastes. This tax policy was simulated by ranging the sludge disposal cost coefficients up to the level at which sludge production was minimized. Whereas Table 1 illustrated the firm's response to Clean Water Act pretreatment standards in the absence of hazardous waste policies, Table 2 illustrates the firm's response to a waste end tax in the absence of pretreatment standards. As would be expected, the results indicate that sludge production is inversely related to disposal costs with a minimum production of 10.6 liters attained at costs above $0.354 per disposed liter. Above $0.354 per liter, however, the percentage of total metals discharged in wastewater increases. In the $0.037 to $0.354 per liter cost range, the nickel concentration exceeds the pretreatment standards and with further increases in disposal costs, nickel and chromium concentration levels are higher and both exceed the pretreatment standards. Even more dramatic is the large increase in the total quantity of residual metals discharged in wastewater. The total load has increased by 170%. Clearly, attempts to reduce solid waste loadings without a corresponding water quality policy simply increase water discharge.

The cross effects of the individual single media management policies are evident in

Table 2. Sensitivity Analysis on Sludge Dilution Costs: Base Model

Coefficient Range ($/liter)	$.037–.354	$.354–1.50
Water Consumption (liters/1040 m2)	2196	2196
Wastewater Production (liters/1040 m2)	1833	1936
Sludge Production (liters/1040 m2)	113.5	10.6
Percentage of Nickel and Chromium in Wastewater	15.00	40.50
Concentrations (mg/liter)		
Nickel	3.18	8.12
Chromium	1.03	2.63
Total Nickel and Chromium in Wastewater (grams)	7.72	20.81

Table 3. Sensitivity Analysis on Sludge Dilution Costs: Pretreatment Model

Coefficient Range ($/liter)	$0–1.02	$1.02–1.50
Water Consumption (liters/1040 m2)	4323	5807
Wastewater Production (liters/1040 m2)	3953	5478
Sludge Production (liters/1040 m2)	120.2	79.8*
Percentage of Nickel and Chromium in Wastewater	15.00	25.50
Concentrations (mg/liter)		
Nickel	1.47	1.80
Chromium	0.48	0.58
Total Nickel and Chromium in Wastewater (grams)	7.71	13.04

* Only 41% of the sludge from the precipitator goes to the vacuum filter.

Table 3. Whereas solely implementing pretreatment standards led to a reduction in the percentage of metals discharged in wastewater, this reduction is blunted by the addition of a waste end tax on sludge production. Previously, water disposal was employed for 15% of total metal residues. Simultaneously implementing a waste end tax creating a disposal cost greater than $1.02 per liter increases water-borne disposal to 25.5%. Waste reduction activities are still employed, but at less than capacity levels. If sludge disposal costs exceed $1.02 per liter, 13.0 grams of nickel and chromium would be discharged in wastewater as opposed to 7.7 grams at lower disposal cost levels.

By comparing Tables 2 and 3, the effects of pretreatment requirements on hazardous waste sludge disposal may be assessed. In the absence of pretreatment (Table 2), sludge disposal costs above $0.354 per liter cause a reduction in sludge production to 10.6 liters. However when both water and land disposal policies are implemented, sludge disposal costs as high as $1.50 per liter still lead to high sludge production levels. Furthermore, by comparing the amounts of wastewater being produced in each of the model runs in all three tables, it can be seen that the highest levels of indirect dilution occur when pretreatment standards are imposed and sludge disposal costs exceed $1.02 per liter. The possibility of indirect dilution raises the issue of the possibility of direct dilution—the addition of fresh water to wastewater to reduce concentration levels. Such an activity is illegal; however, it is not costless to monitor and it may be perceived by the plater as "less expensive or less harmful" than other forms of improper hazardous waste disposal. Even technology-based standards would not prevent this possibility.

Conclusions

A mixed integer programming formulation of a small electroplating job shop has been used to illustrate potential problems with the current mix of environmental policies. Where a pollutant can be discharged into a number of alternative environmental disposal media in a variety of forms, each of which is regulated by a different policy, the optimal discharge rate into each medium is not likely to be achieved even if the regulatory agency has correct knowledge of the appropriate marginal cost and damage curves. For electroplaters, these results indicate an incentive to employ water inefficient rinse systems to minimize the cost of attaining the Clean Water Act's pretreatment standards. If there are incentives for indirect dilution, then there are incentives for direct dilution. Even if direct dilution is not occurring at present, the potential for indirect dilution suggests that policy makers should explore options to provide incentives to platers to adopt water efficient rinse systems.

Various limitations to the model should be mentioned. First, a static model is presented with explicit consideration of uncertainty excluded. Second, we have only considered a small subset of the treatment options available to a plater. From the point of view of policy

makers, perhaps the most important activities left out are illegal activities—improper hazardous waste disposal and midnight dumping. With regard to recycling options, it should be noted that plating bath contamination was not factored into the analysis. Periodic batch dumps might be required when metallic inputs are recycled; ignoring these dumps means that the recovery efficiencies have been slightly overstated. A third limitation particularly significant for small platers is the lack of inclusion of space and capital availability constraints. Fourth, linear treatment costs were assumed, when in reality such costs may be nonlinear. Russell [1973] points out that treatment costs may be S-shaped with declining marginal costs over a significant range. Approximately nonlinear cost functions with linear cost segments is possible, but convexity and the assurance of a global optimum becomes problematic. These problems point the directions that can be taken to extend this research. The creation of a dynamic programming model would add much richness. In particular, there are trade-offs between plating bath immersion duration and concentrations which are important to explore. Finally, adding uncertainty to the model would add considerable realism.

However, none of these limitations is likely to affect the basic message delivered here. Further, the damage costs associated with disposal in alternative media are likely to be much more critical to the determination of an optimal joint management policy. While regulators are concerned with managing damages and firms with costs, economists must be concerned with both. We do not underestimate the difficulty of such joint management across all environmental disposal media; however, some consideration can and should be given to the relative magnitude of damages associated with the choice of disposal medium which includes cross-media effects. At the least, this would indicate which is the more important management target.

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