# Regulation and Control of Hazardous Wastes

HANS W. GOTTINGER*

## 1. INTRODUCTION

The thrust of this paper is motivated by a line of reasoning resembling principal-agent type relationships (ARROW, 1986; REES, 1987). The disposal of hazardous wastes is regulated. The methods, technologies and locations for the treatments of such wastes are stipulated by law. These prescribed methods are costly, and their costs are borne privately by the owners of the wastes. An incentive thus exists for waste owners to break the law, to permit some of their wastes to be improperly released to the environment. The regulator responds by expending social resources on an enforcement program. In effect, having first created a primary incentive for illicit disposal by making the legal option privately costly, the regulator now attempts to raise secondary counter-incentives to suppress the behaviourial response to the primary incentive. These counter-incentives, fines and possibly imprisonment, backed up by the standard law enforcement techniques of patrol, surveillance and investigation, are however imperfect, and illicit disposal proceeds at a strictly positive level. Regulations are not invariable rational, particularly obsolete ones. Toxic waste regulations however, are new, and this paper addresses the case of wastes for which the stipulated disposal methods are socially rational in the sense that the cost to society of having such wastes dispersed to the environment exceeds the costs of interning them in the legally specified manner. For certain classes of these wastes, particularly potent or persistent carcinogens, mutagens, teratogens, the social costs of improper disposal may exceed those of the legal alternative by orders of magnitude (GOTTINGER, 1991). Finally, note that society presently bears the cost of wastes disposed of properly, although it does so implicitly by way of the law-abiding waste dumper's pocket.

The paper is organized as follows;

Section 2 investigates the firm's behaviour, in the first instance we model a waste generating firm's profit maximization problem. The firm's behaviourial responses to various regulatory agency policies are deduced. The firm's profit maximization problem is found to separate into production and waste disposal (criminal) decisions. Section 3 considers the possibilities for the free marketing of hazardous wastes and finds justification for a governmental regulatory agency role. It posits a welfare maximizing agency

* Inst. of Management Science, Univ. of Maastricht (RL) and International Institute for Environmental Economics and Management, Schloss Waldsee, D 88339 Bad Waldsee.
I very much appreciate helpful comments by Professor TERENCE GORMAN and CHRISTOPHER BLISS, Oxford.

and constructs an objective function for such an agency. Optimal behaviour for an agency which is restricted to enforcement policies is deduced in Section 4. In Section 5 behaviourial interaction between the firm and the restricted agency are explored. Implications for agency enforcement policies are drawn in Section 6. Conclusions follow in Section 7.

This analysis focuses on comparative statics. From the societal design of an optimal environmental regime, one should strive for a further reduction of wastes, possibly invoking a waste-free society. Such a view is interesting but not pursued here. It would involve a dynamic long-run consideration of technical change in the waste generating and abating industry.

## 2. THE FIRM'S OBJECTIVE FUNCTION AND BEHAVIOUR

For reasons of simplicity we consider the case of a monopolist who produces a socially desirable output, in quantity y, jointly with an amount w of some hazardous waste. Write the firm's production function as

$$y = y(k,w), \tag{1}$$

where the waste is viewed as an input and k is any conventional input which may substitute for waste in producing the desired output. Further, let p(y), $p' < 0$, be the inverse demand for this output, r be the price of the conventional input, and $\omega$ be the unit of deposing the waste in an agency approved dumpsite. (Assume also the monopolist being a monopolistic supplier of waste).

In a world of perfect or costless agency monitoring and enforcement of firm behaviour, the agency would know if the firm tried to evade the legal disposal fee $\omega$ by covertly dumping part of its waste elsewhere. With this knowledge the agency could simply set a certain fine f of $\omega + \varepsilon$ per unit on any wastes so dumped, making the covert option more expensive than the legal one, thus forcing all wastes into approved dumpsites. Under this scenario of certain punishment the firm's objective reduces to maximizing conventional profit, or

$$\max_{k,w} \{p(y)y - rk - \omega w\} \tag{2}$$

subject to equation (1).

In reality, of course, neither monitoring nor enforcement is either perfect or costless to the agency. The door is opened for illicit dumping by the firm, and some wastes pass through. This is the problem we wish to model. To capture the imperfection assume that the agency's ability to detect, prosecute, and punish the illicit dumper is a binary or

Bernoulli random variable with probability $\pi(\alpha\, w,e,f)$ that the dumper is punished. To capture the costs of the agency's monitoring and litigation effort assume $0 < \pi \leq 1$, $\pi_e > 0$ and $\pi_{e,e} < 0$, so that $\pi$ is a rising, strictly concave function of agency expenditure e. The likelihood $\pi$ that a dumper is caught, for a fixed level of agency effort e, should depend on how much dumping the firm does. Let $\alpha$ be the fraction of its wastes the firm dumps illegally, then the amount so dumped will be $\alpha w$. Assume then that $\pi_{\alpha w} > 0$ and $\pi_{\alpha w,\alpha w} > 0$, so that the probability of being punished is increasing and strictly convex in w. Finally $\pi$ should also depend on the fine, f. EHRLICH [1975] has found, at least in the case of capital punishment versus life imprisonment for convicted murderers, that the probability of punishment is empirically a decreasing function of the punishment's severity. In our case the assumption will be that courts are less likely to impose larger fines. A second rationale for this would be that larger fines call forth a greater legal defence effort on the part of the dumper, which would again lower the probability of his conviction and punishment. Thus, assume $\pi_f < 0$ and $\pi_{f,f} < 0$, so that $\pi$ is a decreasing strictly concave function of the fine magnitude f. We have then that $\pi = \pi(\alpha w,e,f)$

A tenet of our concept of justice is that the punishment should fit the crime. Incorporate this by assuming that convicted dumpers, in addition to the fine, must pay for the complete clean-up, or restoration, of the scenes of their crimes. Let this restoration or repair cost R depend in an increasing and strictly convex way on the quantity of waste w dumped illegally. Specifically assume $R \geq 0$, $R_{\alpha w} > 0$ and $R_{\alpha w,\alpha w} > 0$.

The firm now faces its waste disposal decision: given that it has amount w of waste on its hands, what fraction $\alpha$ of this should it dump illegally? The incentive for choosing $\alpha > 0$ is of course the savings, $\omega\alpha w$, from not paying the legal dump fee $\omega$. This incentive must, however, be traded off against the uncertain prospect of being caught and forced to pay $[R\alpha(w) + f]$, the clean-up and fine, with probability $\pi(\alpha w,e,f)$. Assuming that the firm is risk and ethically neutral, (i.e. placing no intrinsic value on being either criminal or law-abiding), it will solve the problem:

$$\max_{k,w,\alpha} H \equiv p(y)y - rk - \omega(1-\alpha) - [R(\alpha w)+f]\omega(\alpha w,e,f) \tag{3}$$

subject to equation (1). The firm chooses quantities of the conventional input and waste, as well as the disposal of the latter between the legal and illegal options. Law enforcement effort, fines and the fee at the legal dumpsite, the agency's policy instruments, are of now assumed to be taken parametrically by the firm, as is the price r of the conventional input. Substitution of (1) into (3) and differentiation yields the first order conditions necessary for maximization of expected profits:

$$H_k = 0 = (p + p'y)y_k - r, \tag{4}$$

$$H_w = 0 = (p + p'y)y_w - \omega(1 - \alpha) - \alpha[R'\pi + (R + f)\pi_{\alpha w}], \tag{5}$$

$$H_\alpha = 0 = w[\omega - R'\pi - (R + f)\pi_{\alpha w}], \tag{6}$$

where subscripts denote partial derivatives and primes indicate total derivative throughout. Equation (4) has the familiar interpretation that the marginal revenue product of the conventional input equals its price. Equation (5) states that waste is generated until its marginal revenue product equals its marginal cost, where the latter consists of two parts. First, fraction $(1-\alpha)$ of the marginal unit of waste goes to the legal dump at cost $\omega(1-\alpha)$ to the firm. Second, fraction $\alpha$is dumped illicitly, which raises restoration cost by $R'\pi$, hence expected restoration cost by $\alpha R'\pi$, and also increases the probability of detection on the inframarginal illicit dumping by $\alpha\pi_{\alpha w}$, hence expected restoration cost by $\alpha\pi_{\alpha W}(R+f)$. Equation (6) represents the waste disposal decision. For positive y and w this requires

$$\omega = R'\pi + (R + f)\pi_{\alpha w} \tag{7}$$

We have just analyzed the right-hand side as the increment to expected cost from dumping a marginal unit of waste illegally. The left hand side is the cost of disposing of one unit at the legal dump site. Thus (6) and (7) require waste to be dumped illegally until the firm is indifferent in an expected cost sense between these two options.

Consider now the behaviour of the increasing, strictly convex function of $\alpha w$, $\pi(\alpha w,e,f)$, in the neighbourhood of $\alpha = 0$. With no illegal dumping, $\alpha = 0$, there is no risk of punishment, so that $\pi(0,e,f) = 0$, and equation (6) becomes:

$$H_\alpha |_{\alpha=0} = w[\omega - (R + f)\ \pi_{\alpha w}\ (0,e,f)]. \tag{8}$$

The crucial but plausible assumption is now made that $\pi_{\alpha w}(0,e,f) = 0$ also. That is, that the slope of $\pi$ over the $\alpha w$ axis is zero for $\alpha = 0$. The intuition is that with $\alpha$ and hence $\alpha w$ sufficiently small, the waste itself, and hence the crime, would be undetectable. (The firm can, say, flush one single molecule of its waste down the sewer risklessly.) Equation (8) now becomes:

$$H_\alpha |_{\alpha=0} = w\omega > 0\ . \tag{9}$$

Two important implications of the model may be drawn immediately from this result. First, the ethically neutral firm will dump waste illegally in strictly positive amounts. That is, the model has descriptive power *vis à vis* the documented fact that some firms do dump hazardous wastes illegally. Second, equation (9) is independent of the levels of the fine, f, and agency monitoring and enforcement expenditure, e. The upshot is the very strong implication for policy which is that no finite level of fine or agency effort will completely eliminate the illegal disposal of hazardous waste.

**Table 1: Comparative statics signs for the firm**

| variable firm adjust | $\frac{d}{df}$ | $\frac{d}{de}$ | $\frac{d}{d\omega}$ |
|---|---|---|---|
| k | 0 | 0 | ± |
| w | 0 | 0 | – |
| α | – | – | + |
| αw | – | – | + |
| y | 0 | 0 | ± |

The firm's profit maximizing responses to changes in the parameters are derived in the Appendix and summarized in Table 1. Conclusions to be drawn from this table include the intuitive and reassuring results that increased fines or agency enforcement effort do reduce illegal dumping, both in absolute quantity $\alpha w$ and in proportion ($\alpha$) to waste generated. Equally intuitive but less comforting are the two + signs in the right-hand column of the table, which show that increases in the fee charged at the legal dumpsite encourage more illegal dumping both absolutely $\frac{\delta(\alpha w)}{\delta \omega} > 0$, and relative to legal disposal, $\frac{\delta \alpha}{\alpha \omega} > 0$.

The legal dump fee $\omega$ lies at the heart of the waste disposal decision. It is in fact the positive, primary incentive for illegal dumping. The agency's other policy instruments, e and f, of course influence the firm's disposal decision, but they are only second order counter-incentives, in effect serving as partial disincentives to the primary incentive $\omega$. Analysis of this primary instrument, its role in incentive compatibility, enforceability, and the social optimality of hazardous waste regulation are subsequently developed.

## 3. THE AGENCY'S OBJECTIVE

Having thus rationalized a role for governmental intrusion into the private sector's freedom regarding these wastes, let us construct a formal model of a regulatory agency's interests and behaviour. Assume its objective is to maximize the social welfare (denoted by L), its attitude towards risk to be one of neutrality. Define social welfare as the simple additive composition of three elements: consumer surplus (CS) in the market for the firm's desired output y, producer's surplus (PS) or profit in the same market, and finally, what will be called *the agency's surplus* (AS), into which we shall gather all welfare impacts residual to the first two elements. Thus,

$$L \equiv CS + PS + AS. \tag{10}$$

Of these three components the first, consumer's surplus, presents the least difficulty. The desirable output y is a good, its quantity and price are known with certainty, even if the actual *ex post* cost of waste production to the firm is not. To a first approximation the net benefits to consumers from he existence of the market for this desirable output y may be taken to be measured by

$$CS \equiv \int_0^Y P(q)\,dq - P(y)\,y, \tag{11}$$

where $P(\cdot)$is the inverse market demand for the output, and y is the quantity trade VARIAN [1978, p.221]. The accuracy of this measure of course supposes the marginal utility of income for each consumer to vary only negligibly over income ranges on the order of that consumer's share of CS. The deterministic nature of this component assures that the assumption of agency risk-neutrality is thus far without any loss of generality.

The second contribution to welfare is producer's surplus or profit. This component was treated from the firm's perspective in the preceding section, where it was assumed to be given by:

$$PS \equiv P(y)y - rk - \omega(1-\alpha)w - [R(\alpha W) + f]\pi(\alpha w,e,f). \tag{12}$$

This quantity is of course random, with both the outcome payoffs and the probabilities of these assumed to be known to the firm. Granting the agency full knowledge of demand and the production functions for y, these payoffs and probabilities become known to it as well.[1] The agency's problem is thus one of decision-making under risk, at least for the sum of these first two components of the social welfare. Having previously taken the firm to be risk-neutral towards its profit, it seems appropriate for the agency to adopt this attitude as well when adding this second element into its welfare measure, since it is after all the firm's welfare which this element is meant to reflect.

1. WEITZMAN [1974], KWEREL [1977], BARON and MYERSON [1982] and others treat some of the problems faced by regulators not knowing the firm's costs and hence its profits as given by equation (11) of the text.

A moment's attention to equation (12) does however raise one objection. If the firm were perfectly law-abiding, it would set $\alpha = 0$. Its profit would then be certain, and given by:

$$PS(\text{legal firm}) = P(y)y - rk - \omega w. \tag{13}$$

The ethically neutral firm can do better than (13) by breaking the law and setting $\alpha > 0$ as was shown to occur in Section 2. The criminal firm saves legal dump fees in amount $\omega\alpha w$, but bears the expected cost of its crime in amount $[R(\cdot) + f]\ \pi(\cdot)$with a net private gain from its dirty deed, which will be termed its *ill-received gains*, equal to

$$IRG = \omega\alpha w - [R(\cdot) + f]\ p(\cdot) > 0. \tag{14}$$

This return to crime is just the difference between equation (12) and (13). Expression (14) holds as a strict inequality, provided only that the quantity of waste w produced by the firm and the fee $\omega$ charged at the legal dumpsite are both strictly positive.[2] Equation (12), which is our candidate for inclusion into the agency's index of social welfare, thus counts these ill-received gains as a positive contribution to society's well-being. Reasonable citizens besides G. STIGLER [1970] may well object to this convention on general principles. More tolerant or charitable ones, including G. BECKER [1968], A.M. POLINSKY and S. SHAVELL [1984], and T. SCHELLING [1984], by accepting this convention seem to grant that even criminals' consumptions have social merit, regardless of how they are financed. The perspective taken here is that crime is an economic activity the gains from

2. Assume $\omega > w > 0$ and profit maximizing firm behaviour. Then $w = w^*$ satisfies (5), and $\alpha^*$ is strictly positive by the discussion following (9), so that $\alpha w^* > 0$. The marginal expected gain to the firm from illicitly dumping another unit of the waste is just the derivative of (14) with respect to $\alpha w$:
(i) $IRG'(\alpha w) = \omega - [R'(\alpha w)\ \pi(\alpha w,\cdot) + [R(\alpha w) + f]\ \pi_{\alpha w}(\alpha w,\cdot)]$
We hold e and f constant here, so that $_w$ temporarily denotes a total derivative. The slope of this marginal gain function is
(ii) $IRG''(\alpha w) = -[R'\pi + 2R'\pi_{\alpha w} + (R + f)\pi_{\alpha w,\alpha w}] < 0$.
The sign of (ii) follows from (A4) of the Appendix. $IGR'(\alpha w)$ thus falls monotonically in $\alpha w$. Now the portion of (i) inside the braces is zero for $\alpha w = 0$ by the discussion surrounding expression (8) of the text in Section 2, so that $IRG'(0) = \omega > 0$. Furthermore, the right-hand side of (i) is zero for $\alpha w = \alpha w^*$ by (6). Since $IRG'(\alpha w)$ is monotonic, for $0 < \alpha w < \alpha w^*$ we must have $IRG'(\alpha w) > 0$ for $\alpha w$ within this domain, with equality holding only at the upper limit, that is at $\alpha w - \alpha w^* > 0$. Now

$$IRG = \int_0^{\alpha w^*} IRG'(\alpha w)d(\alpha w) > 0,$$

because the integrand is strictly positive except at its upper limit, over a domain of strictly positive measure. The sign of inequality (14) is thus established.

which, to whoever they accrue, should be reckoned into social welfare along with the costs.

The third and final component of social welfare, the agency's surplus (AS), consists of four parts itself: the environmental damage due to improper dumping which falls by assumption on people external to the production and consumption decisions, the agency's own consumption of resources in its monitoring and enforcement activities, surplus in the legal dump industry which may be negative to allow for government subsidization of the dump fee, and finally a term to account for revenues to the treasury due to fines collected from convicted criminal dumpers. Consider these now in detail.

The environmental damage resulting from illicit dumping is the most interesting and important part of the entire model. It is also the most difficult to treat formally in a satisfactory manner. For most hazardous substances, hence wastes, little is known of their long-term physical effects on people and their interests. One thus has obvious difficulty attaching probabilities to these unknown outcomes, and the agency is seen to face this important decision under conditions worse even than uncertainty. Consider a mapping from this space of unknown physical consequences of illegal dumping into their monetary costs in terms of environmental damage, and let the latter be the outcome space. These outcomes are still unknown but now at least defined on the positive real line. Of course, we still lack a set of even subjective probabilities over the range of this new outcome space, but if we did have or were willing to assume one, we could bring the analytical tools of the theory of decision making under risk directly to bear on the problem. Let us therefore assume that the agency has in hand a distribution of at least subjective probabilities over the range of possible money costs associated with the environmental consequences of improperly dumped hazardous wastes. This last step is the crucial one. Carrying things one relatively small step further with the stronger assumption that this postulated probability distribution is degenerate simplifies the analysis considerably at only a second order additional sacrifice of realism.

To summarize, it is assumed that a money value, $D(\alpha w)$, known with certainty, can be attached to the environmental damage resulting from the improper disposal of an amount w of the hazardous waste. If the dumper is not caught, which occurs with probability $1 - \pi$, hence not forced to repair the site of his crime, this damage will be sustained. The first of the four components of the agency's surplus will thus be

$$- D(\alpha w)\,[1 - \pi(\cdot)]. \tag{15}$$

the random money value of the environmental damage.

Two of the remaining three contributions to the agency's surplus are straightforward. First, the agency should account for its own expenditure of society's resources, e, in its monitoring and enforcement efforts. Second, it should also account for any fines collected from convicted offenders. The treasury expects to gain an amount f with probability $\pi$ on this score. These two considerations combined enter the agency's surplus as the random quantity

$$-e + f(\pi)\,(\cdot). \tag{16}$$

Finally, we allow for the option of subsidization of the legal dump fee $\omega$, and thus for agency manipulation of the primary incentive for illegal dumping in the first place. Let $C(l)$ denote the costs of interning an amount $l$ of the waste in the legally prescribed manner, where $C(l)$ is assumed to be increasing and convex. Having dumped quantity $\alpha w$ of its waste illicitly, the firm delivers the balance, $(1\text{-}\alpha)w$, to the legal dumpsite, contributing an amount $\omega(1-\alpha)w$, towards the operating costs of the legal dump, which are in total $C[1-(\alpha)w]$. The difference between these,

$$\omega(1-\alpha)w - C[(1-\alpha)w], \tag{17}$$

is then the final contribution to the agency's surplus. If (17) is positive we are accounting for profits in the waste dump industry as an addition to the agency's surplus, if negative the government is assumed to be subsidizing the legal disposal option and (17) then subtracts the amount of this subsidy from social welfare by way of the agency's surplus. The agency's surplus (AS) is thus the sum of equations (15), (16) and (17):

$$AS \equiv -D(\alpha w)\,[1-\pi(\cdot)] - e + f\pi(\cdot) + \omega(1-\alpha)\,w - C[(1-\alpha)]. \tag{18}$$

If the agency is now risk-neutral with respect to its own surplus, it must also be so for the social welfare, as such an attitude has already been rationalized for the other two elements of its welfare index. Expected social welfare, L, recalling equation (10), is the sum of the consumer's, producer's and agency's surpluses, hence the sum of equations (11), (12), and (18), which after cancellations yields:

$$\begin{aligned} L \equiv & \int_0^Y P(q)\,dq - rk - R(\alpha w,e,f) \\ & -D(\alpha w)\,[1-\pi(\alpha w,e,f)] - e - C[(1-\alpha)w]. \end{aligned} \tag{19}$$

We observe that both the expected fine, $f\pi$, and the firm's contribution to the costs of operating the legal dumpsite, $\omega(1-\alpha)w$, have dropped out of equation (19) as considerations in social welfare. The interpretation is immediate and intuitive. Both of these quantities merely represent transfers from the producer's surplus to that of the agency, hence neither affects welfare in the aggregate. The agency is properly indifferent to their magnitudes, and we would have been concerned had they not disappeared from equation (19).

The risk-neutral regulatory agency will now proceed to maximize the social welfare subject to the constraints imposed by the functions P (·), R (·), π (·), D (·) and C (·).

## 4. THE RESTRICTED AGENCY'S BEHAVIOUR

In view of likely institutional settings we follow the scenario of an agency facing relatively severely constrained options.

Suppose that the waste dump fee is set at $\hat{\omega}$ by market forces in the respective industry, that the fine is fixed at $\hat{f}$ by the legislature and courts, and that each of these is taken parametrically by both the agency and by the waste generating firm. Let us refer to this highly constrained agency, which has discretion over only the single policy variable e, as the "restricted" agency. Finally we need to specify an agency conjecture of how the firm might react to its own policy changes, for this will certainly have an important bearing on which policy the agency will prefer.

When treating the firm's profit maximization problem, it was assumed that the firm took the agency's policy (e, f, ω) parametrically. The practical significance of this was that the firm could neglect any agency response to its own actions. This Cournot conjecture was reasonable, even for our monopolistic firm, since being the entire industry of the desired output y in no way precludes its production of the waste w from being a negligible fraction of the total economy-wide supply of this waste.

A similar Cournot conjecture for the agency's problem is less easily justified. The agency is after all a regulatory power by design, its very *raison d'être* presupposing an ability to influence firm behaviour. This assumption, that the restricted agency neglects the impacts of its own policy (e) on the actions of the firm (α, k, w), will nevertheless be invoked temporarily for several reasons. First, this policy is feasible. Nothing prevents the agency from ignoring its own influence. We shall see later that it may wish to do just this in the social interest. Second, this naive Cournot behavioural supposition yields insights into the agency's problem. Third, it is a stepping stone to more sophisticated agency behaviours. Fourth, it requires very little information to implement. And finally, since it is feasible, it provides one achievable welfare outcome which can be used as a yardstick for comparing outcomes resulting from alternative agency conjectures.

Suppose then that the restricted (to e policies only) agency chooses e so as to maximize expected social welfare, subject to these functional, institutional and behavioural constraints. Its problem may be stated formally as:

$$\max_{e} L \tag{20}$$

where L is given by equation (19). The first order necessary condition for social welfare to be at a maximum is:

$$L_e = [D(\alpha w) - R(\alpha w)]\pi_{e'}(\alpha w, e*, \hat{f}) - 1 = 0. \tag{21}$$

where $e* = e*(\alpha w, \hat{f}, \hat{\omega})$ denotes the optimum level of agency enforcement expenditure. Further differentiation of (21) with respect to e gives:

$$L_{e,e} = [D(\alpha w) - R(\alpha w)]\pi_{e,e}(\alpha w, e*, \hat{f}) < 0, \tag{22}$$

provided (D-R) > 0. That is, provided that cleanup of improperly dumped waste is socially rational, second order sufficient conditions for $e^*$ to yield a welfare maximum are satisfied. Equation (21) may be restated as:

$$[D(\alpha w) - R(\alpha w)]\pi_e(\alpha w, e*, \hat{f}) = 1, \tag{23}$$

By the Cournot assumption the level of e has no impact on the quantity $\alpha w$ of waste being dumped illegally, which is a firm behaviour. Hence e affects only the probability $\pi(\cdot)$ that the criminal dumper is caught, convicted and forced to clean up the site of his invariant level of illicit disposal. Equation (23) thus says that the agency should expend society's resources on enforcement until the marginal cost of this, on the right hand side of (23), benefits society with a marginal expected money's worth of environmental damage (net of clean up cost) repaired on the left.

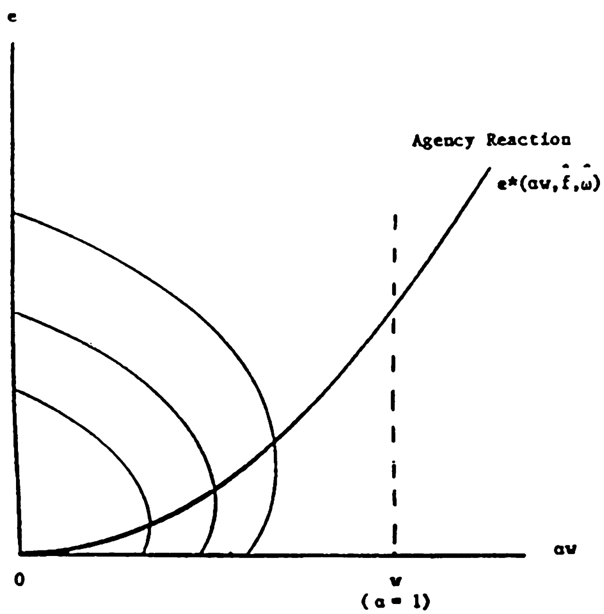
Consider now this restricted agency's welfare maximizing response to changes in the firm's dumping behaviour. If the firm alters $\alpha w$ slightly, the agency will adjust $e^*$ so as to reestablish relation (21). Total differentiation of this relation with respect to $\alpha w$ and $e^*$, upon rearrangement yields,

$$\frac{de^*}{d(\alpha w)} = \frac{(D' - R')\,\pi_e + (D - R)\,\pi_{\alpha w,\,e}}{-\,(D - R)\,\pi_{e,\,e}} > 0.$$

The intuition is plain. Higher levels of illicit dumping by the firm raise the marginal benefit of enforcement at the present level of $e^*$, the marginal cost remains constant at 1, the agency responds with greater expenditure. The restricted agency's Cournot reaction function thus has the positive slope given by (24) and displayed in Figure 1.

This function must intercept the origin of e-$\alpha w$ space, point 0, which represents the global maximum welfare scenario of no illicit dumping combined with the optimal agency reaction to this of no expenditure of social resources on enforcement. This reaction function is drawn in the figure departing from the origin with a slope of zero, which reflects the earlier assumption that perfectly law abiding firms enjoy their first minute taste of crime without risk, i.e. that $\pi = \pi_{\alpha\omega} = 0$ for $\alpha w = 0$ and e and $\hat{f}$ at arbitrary but finite levels. This then implies that $\pi_e = \pi_{\alpha w,e} = 0$ for $\alpha w = 0$, which in turn suggests that for $\alpha w$ near zero agency enforcement expenditures are unproductive in the sense of generating apprehension probability, and hence that the change in $e^*$, as $\alpha w$ rises from zero, is initially zero as well. Formally this amounts to $\frac{de*}{d(\alpha w)}|_{\alpha w=0} = 0$.

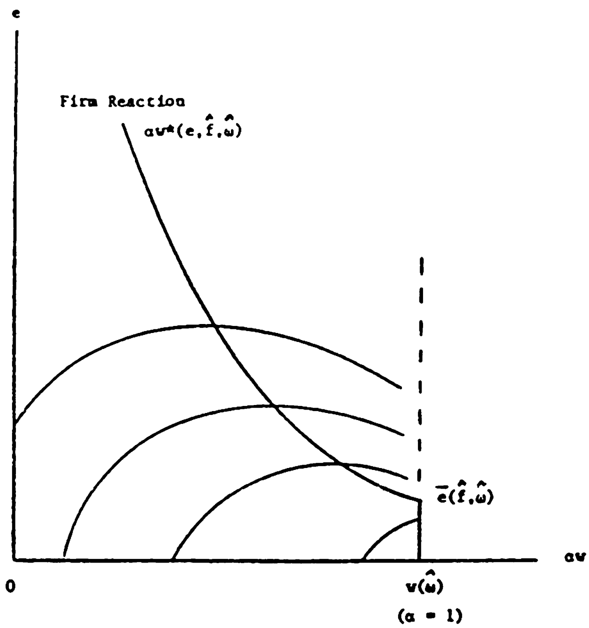
**Figure 1: Agency Enforcement Expenditure Reaction to Firm Dumping Behaviour**



## 5. RESTRICTED AGENCY-FIRM INTERACTIONS

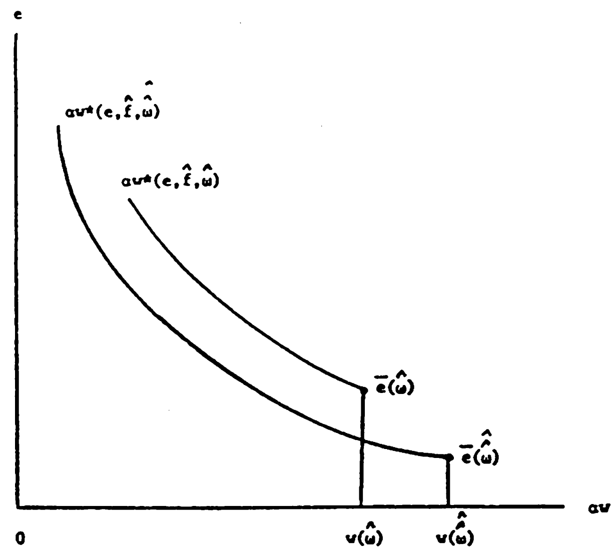
The firm's Cournot reaction path is displayed in Figure 2. Points on this function represent the profit maximizing level of illicit dumping ($\alpha w^*$) associated with each level of agency enforcement expenditure. This figure also depicts several contours of the firm's profit function.

**Figure 2: Firm Dumping Reaction to Agency Enforcement**




This reaction function's negative slope is derived in equation (A18) of the Appendix. It exhibits an asymptotic approach to the e axis to reflect the earlier result that the firm will choose $\alpha w^* > 0$ for any finite level of e. Lower levels of enforcement mean lower expected costs to the firm for illicit dumping, and no enforcement at all (e = 0) makes illicit dumping, hence the waste input, free. Point w ( $\hat{\omega}$ ) on the horizontal axis is the global profit maximum for fixed $\hat{\omega}$. Point w ( $\hat{\omega}$ ) is independent of e and $\hat{f}$ to reflect the results (A11) and (A16) of the Appendix that $\frac{dw^*}{de}$ and $\frac{dw^*}{df}$ are both zero. Point w does however depend on $\hat{\omega}$, with higher $\hat{\omega}$ shifting w to the left, consistent with result (A21)

**Figure 2A: Effect of a Fall in the Dump Fee on the Firm's Dumping Reaction to Agency Enforcement**



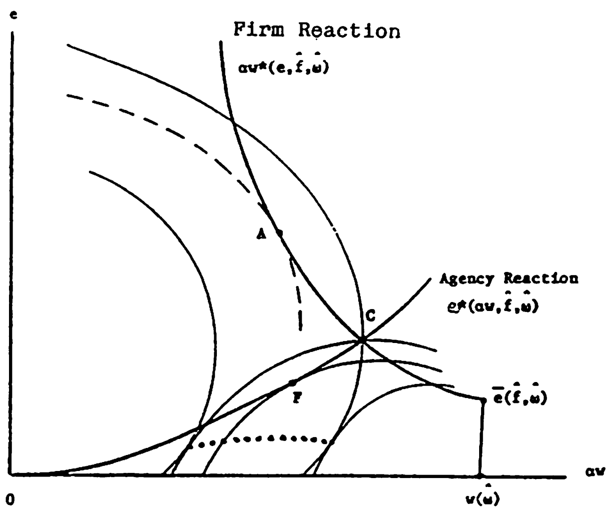

Note: $\hat{\hat{\omega}} < \hat{\omega}$.

that $\frac{dw^*}{d\omega} < 0$. The curve as drawn reflects the possibility that the firm may dump all its waste illicitly [$\alpha = 1$ implies $\alpha w = w = w(\hat{\omega})$] for enforcement expenditure below some small but positive level $\bar{e}(\hat{f},\hat{\omega})$. Holding e constant, higher $\hat{f}$ and lower $\hat{\omega}$ make illicit dumping less profitable for the firm, as seen from the results (A13), that $\frac{d(\alpha w^*)}{df} < 0$, and (A24), that $\frac{d(\alpha w^*)}{d\omega} > 0$, of the Appendix. The effect of higher $\hat{f}$ on the firm's dumping reaction function, $\frac{d(\alpha w^*)}{df} < 0$, is thus a combination of a leftward or downward shift and/or a counterclockwise rotation, so that w falls horizontally to the left a every (constant) value of e along the function. Since $\frac{dw^*}{df} = 0$ by (All), point $\bar{e}(\hat{f}, \hat{\omega})$ drops vertically above the stationary point $w(\hat{\omega})$ as $\hat{f}$ rises, until the $\alpha w$ axis is reached, after which the rotation continues. The effects of lowering $\hat{\omega}$ to $\hat{\omega}$ on the function are twofold, and are illustrated in Figure 2A. First, $\frac{dw^*}{df} < 0$ means point $w(\hat{\omega})$ moves rightward along the horizontal axis as $\hat{\omega}$ falls. Second, for points at which we have internal solutions

($\alpha < 1$) both before and after the dump fee falls from $\hat{\omega}$ to $\hat{\omega}$, $\frac{d(\alpha w^*)}{d\omega} > 0$, requires that the reaction function shift and/or rotate leftward or downward as $\hat{\omega}$ falls, so that point $\bar{e}$ shifts downward as it moves rightward along with and vertically above point $w(\hat{\omega})$.

The agency's and firm's Cournot reaction functions are combined in Figure 3. Bear in mind that welfare is maximized at the lower left corner, firm profits at the lower right. Point C in Figure 3 locates the intersection of the two reaction functions, hence the Nash-Cournot equilibrium. This point must be unique by virtue of the opposing and strict monotonicities of the two functions involved. The stability of this equilibrium requires that the (absolute value of the) slope of the firm's reaction function exceed that of the agency's in the neighbourhood of point C.

**Figure 3: Firm Dumping Behaviour – Agency Enforcement Interactions Legend**




A ≡ Stackelberg leader agency.
C ≡ Cournot solution.
F ≡ Stackelberg leader firm.
O ≡ Global welfare optimum.
$w(\hat{\omega})$ ≡ Global profit maximum, $\hat{\omega}$ fixed.
---- ≡ Critical welfare isoquant.
.... ≡ Negotiable portion of contract curve.

## 6. POLICIES FOR THE RESTRICTED AGENCY

The basic policy recommendation for the restricted Cournot agency would be for it to recognize that the firm will in fact respond behaviourally to its enforcement policies. The agency should abandon its Cournot conjecture and the behaviour thereby implied. Alternative superior feasible conjectures include those of both the Stackelberg leader agency, at point A in Figure 3, and the follower agency (leader firm) at point F.

The superiority of both these alternatives to the Cournot solution follows from inspection of the figure, in which both points A and F lie on higher welfare isoquants than does point C. Point A, on the firm's reaction function, results from the agency maximizing social welfare subject to the conjecture that the firm remains Cournot, and the firm following, adopting on its part just that Cournot conjecture which the agency attributed to it. The result is an equilibrium at point A in which each party's conjecture of the others's behaviour is realized. Point F results from the symmetric case of the Stackelberg leader firm and follower agency, in which these conjectural roles are reversed.

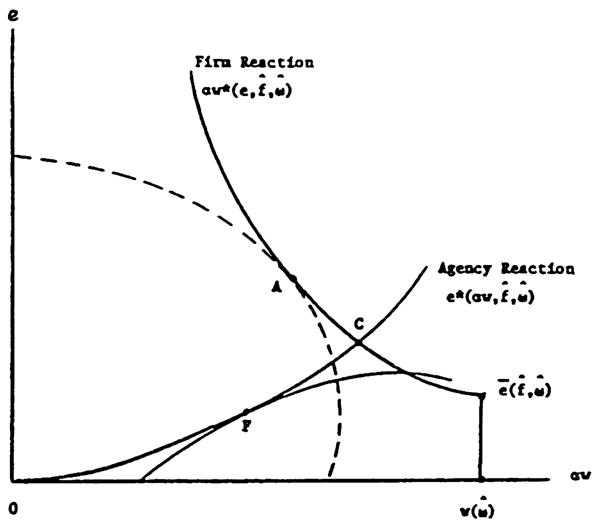
In surprising contrast to the generally indeterminate case of the market duopoly, where Stackelberg conjectures need not be realized, is the fact that both points A and F represent feasible agency policies. That is, unlike the case of a market duopolist, the regulatory agency can bend the firm's conjecture to suit its own preferences, force the latter's behaviour to either of these points at its own will.

First, observe that the firm's profits descend monotonically from point F to C to A, so that its preferences run in just this order. Second, recall the policy relevant point raised above that welfare is higher at either A or F than at C. Third, the relative desirabilities of points A and F in terms of welfare depend on whether the dashed critical welfare isoquant passing through A in the figure intersects the agency reaction path to the left or right of point F, an issue which is unresolvable without further restriction of the model.

Sufficient for F to be welfare superior however is the case in which point A lies due north or northeast of F. Intuitively, if the aggressive (Stackelberg leader) agency solution (point A) requires greater enforcement spending (A north of F) while illicit dumping does not fall (A not west of F), welfare must suffer. Since actual dumping behaviour is observable in the long run, agency experimentation with these two policies would reveal whether or not point A in fact does lie to the right of F. If it does the agency enforcement problem is solved. It should adopt the passive, Stackelberg follower strategy F.

A subcase in which point A falls strictly rightward of F merits particular attention, and is illustrated in Figure 3A. This analysis suggest that a small (low e budget, few investigators, lawyers, clerks), passive, Stackelberg follower agency policy may result in not just greater welfare than the large, aggressive, Stackelberg leader agency strategy, but surprisingly in less illicit dumping. This policy's pertinent possibility seems counter intuitive. Relaxed enforcement results in less dumping. This unexpected finding appears counterintuitive only because it reverses the actual line of causality. In moving from the solution at point A to that at point F the firm becomes the Stackelberg leader, and is endowed with a much richer information set that it enjoyed as a follower. The leading firm knows the agency's entire reaction function, most importantly its positive slope. The firm reduces its illegal dumping *not because* the agency has cut its enforcement effort, but because it knows that this will *induce* the agency to cut its enforcement effort.

**Figure 3A: Lower Enforcement May Lead to Less Criminal Dumping**




The second case, in which point A is found to lie to the left of F, is not symmetric. It does not imply that welfare is higher under the leader agency strategy at point A. The level of illicit dumping falls, relative to point F, but expenditures will have risen. Whether society gets its money's worth in terms of reduced dumping is the issue, one which cannot be decided on the basis of this qualitative theoretical analysis plus observations on $\alpha$w. A definitive answer would require estimation of the specific functions involved (which for D($\alpha$w) certainly runs beyond the present body of scientific knowledge), or else a political judgment by society.

It was asserted that both Stackelberg strategies A and F are feasible agency policies. Suppose the agency wished to enforce solution F, at which the firm leads, say because the agency has determined or assumed that the dashed critical welfare isoquant in Figure 3 intersects its reaction function above point F. The agency needs only publish its reaction function, ensure that the firm knows what level of enforcement it will respond with to each level of illegal dumping. This Cournot agency behaviour, characterized by its reaction function, is perfectly feasible for the agency. Nothing prevents it from *acting as if* firm behaviour were invariant with respect to its own actions, whether or not this is in fact its true conjecture. There is no conflict. The agency follows. Since the firm's profits are higher at F it will be happy to oblige by adopting the Stackelberg leader conjecture and behaviour. The mutual realization of conjectures is established, equilibrium at point F will result.

Demonstrating the feasibility of the solution at point A is only slightly less trivial. Profits are lowest here, so the firm will not willingly adopt the Stackelberg follower conjecture unless the agency can force it to. In the duopolistic market context the result would be "Stackelberg warfare", incompatible conjectures with both parties attempting to lead, and a generally indeterminate outcome. Replacing one duopolist with a regulatory agency makes a difference. Its ability to impose the Stackelberg solution at A with itself as the leader and a following firm stems from the fact that it is not in the game for profit, which gives it a sort of strong advantage over the firm. The agency can simply set the level of its enforcement expenditure at that given by the vertical distance to point A, and keep it there indefinitely. In the market duopoly case the (other) firm need not comply by maximizing profits subject to this as a constraint if it thought its opponent (the agency here) were suffering sufficiently to eventually abandon its attempt to lead. For the non-profit-making agency however the expenditures associated with point A are sustainable quite independently of the firm's behaviour, and the firm knows this, so that it will eventually move to point A as well in order to maximise its profits given this agency behaviour.

None of the three solutions investigated thus far allows for the possibility of cooperation between the firm and agency, that is for negotiated solutions. The dotted curve at the bottom of Figure 3 illustrates the potential for mutual gains when the initial solution is at point C. A similar curve exists for each of the other two initial points. These are not drawn in the figure, but would lie to the south and west of points A and F respectively. One might imagine such cooperation in the form of a bargain in which, starting from A, C or F, the firm agrees to restrain the illicit dumping in exchange for a commitment from the agency to reduce its enforcement effort. Society would gain, both via a reduced level of environmental damage and from enforcement expenditures saved. The firm would curtail its illicit dumping but at a level of risk sufficiently reduced by the lower agency enforcement to compensate for this lower volume. With this prospect for mutual gains as a lure, the question arises as to the feasibility of such a bargain.

The answer would seem to be in the negative on political grounds, due to the Faustian nature of such a pact. It is hard to imagine the public tolerating the reward of criminal dumpers with relaxed enforcement even in exchange for a reduced level of their dirty deeds.

## 7. CONCLUSIONS

We modelled a profit maximizing, hazardous waste generating, monopolistic firm, a welfare maximizing regulatory agency, and investigate their behavioural interactions.

Our analysis of agency-firm interactions over the enforcement effort policy variable yields the following results. In contrast to the generally indeterminate case of interacting market duopolists, the Stackelberg leader and follower agency strategies are both unilaterally enforceable by the agency. They are therefore both feasible policies for the agency. Both the leader and follower agency strategies are welfare superior to the Cournot. That welfare may be greater with a low enforcement budget, a Stackelberg follower agency scenario, than with a larger, more expensive Stackelberg leader agency, is not surprising. Unexpected however is our finding that less illicit disposal may occur with the smaller following agency. Finally, we conclude that the agency wishes a maximal flow of information between itself and the firm. While the firm will not generally be forthcoming to the agency about its illicit dumping behaviour, the agency should nevertheless communicate its own policies clearly to the firm.

### APPENDIX

#### Comparative statics for the monopolistic firm

The monopolist's objective is:

$$\max_{k,w,\alpha} H \equiv p(y)y - rk - \omega(1-\alpha)w - [R(\alpha w) + f]\pi(\alpha w, e, f). \tag{3}$$

Second order sufficient conditions for the expected profit maximization require that $|H..| < 0$ in the neighbourhood of the solution, $(k^*, w^*, \alpha^*)$, where

$$[H..] \equiv \begin{bmatrix} H_{kk} & H_{kw} & H_{k\alpha} \\ H_{wk} & H_{ww} & H_{w\alpha} \\ H_{\alpha k} & H_{\alpha w} & H_{\alpha\alpha} \end{bmatrix} = \begin{bmatrix} H_{kk} & H_{kw} & 0 \\ H_{wk} & H_{ww} & -\alpha wc \\ 0 & -\alpha wc & -w^2 c \end{bmatrix} \tag{A0}$$

$$\begin{bmatrix} (ay_{kk} + by_k^2) & (ay_{wk} + by_w y_k) & 0 \\ (ay_{wk} + by_w y_k) & (ay_{ww} + by_w^2 - \alpha_w^2 c) & -\alpha wc \\ 0 & -\alpha wc & -w^2 c \end{bmatrix}$$

$$|H..| < 0 \tag{A1}$$

by the assumption that second order sufficient conditions are satisfied.

$$a \equiv p + p'y = MR. \tag{A2}$$

$$b \equiv 2p' + p''y = MR'. \tag{A3}$$

$$c \equiv R''(\alpha w)\pi + 2R'(\alpha w)\pi_{\alpha w} + [R(\alpha w) + f]\pi_{\alpha w,\alpha w} > 0 \tag{A4}$$

by the assumption in (A1), or alternatively by the previous assumptions that $R(\cdot)$ are increasing and strictly convex in $\alpha w$. The following definitions and assumptions will be useful presently.

$$d \equiv R'(\alpha w)\pi_f + \pi_{\alpha w} + [R(\alpha w) + f]\pi_{f,\alpha w} > 0 \tag{A5}$$

by assumption. d is just the cross partial derivative of the expected penalty for illicit dumping with respect to $\alpha w$ and f. (A5) simply asserts that the level of the fine is not so high that the court's hesitancy to impose it at the margin (the first and third terms in (A5) are $< 0$) outweighs the increased risk to the firm (the second term, $\pi_{\alpha w} > 0$) from marginal illegal dumping. That is, the marginal expected punishment due to marginal illegal dumping is assumed to be increasing in the fine. Clearly any fine which is rational in the sense that it acts as a deterrent rather than an inducement to marginal illicit dumping will be set so that $d > 0$.

$$g \equiv R'(\alpha w)\pi_e + [R(\alpha w) + f]\pi_{\alpha w,e} > 0. \tag{A6}$$

This follows from previous assumptions on $R(\cdot)$ and $\pi(\cdot)$, together with the assumption that $\pi_{\alpha w,e} > 0$, i.e. that the marginal risk of being caught due to increased illegal dumping rise with increased agency effort or expenditure, e.
Expanding (A1) yields:

$$|H..| = -w^2c(H_{kk}^2H_{ww} - H_{wk}^2) - (\alpha wc)^2H_{kk} < 0. \tag{A7}$$

Second order sufficient conditions require the principal minors of order 2 be positive, hence that

$$H_{kk}H_{ww} - H_{wk}^2 > 0. \tag{A8}$$

Total differentials of the first order conditions, equations (4), (5) and (6) of the text, with respect to the parameters f, $\omega$, and e may be expressed as:

$$[H..]\begin{bmatrix} dk \\ dw \\ d\alpha \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ \alpha d & (1-\alpha) & \alpha g \\ wd & -w & wg \end{bmatrix} \begin{bmatrix} df \\ d\omega \\ de \end{bmatrix}. \tag{A9}$$

The firm's comparative static adjustments of $k^*$, $w^*$ and $\alpha^*$ in response to changes in the parameters f, $\omega$ and e may now be found using Cramer's rule:

$$\frac{dk^*}{df} = \frac{\begin{vmatrix} 0 & H_{wk} & 0 \\ \alpha d & \text{—} & (-\alpha wc) \\ wd & \text{—} & (-w^2c) \end{vmatrix}}{|H..|} = 0, \tag{A10}$$

due to linear dependence between the first and third columns of the numerator.

$$\frac{dw^*}{df} = \frac{\begin{vmatrix} H_{kk} & 0 & 0 \\ H_{wk} & \alpha d & (-\alpha wc) \\ 0 & wd & (-w^2c) \end{vmatrix}}{|H..|} = 0, \tag{A11}$$

as the second and third columns are again linearly dependent.

$$\frac{d\alpha^*}{df} = \frac{\begin{vmatrix} H_{kk} & H_{wk} & 0 \\ H_{wk} & H_{ww} & (\alpha d) \\ 0 & -\alpha wc & (wd) \end{vmatrix}}{|H..|} = \frac{\frac{-d}{wc}|H..|}{|H..|} = \frac{-d}{wc} < 0, \tag{A12}$$

since the last column of the numerator equals $\frac{-d}{wc}$ times the last column of [H..], the first two columns of the numerator and denominator are identical, and d, w and c are all positive. For the sake of notational parsimony we shall write $\alpha w^*$ in place of $\alpha^* w^*$ throughout.

$$\frac{d(\alpha w^*)}{df} = \alpha^* \frac{dw^*}{df} + w^* \frac{d\alpha^*}{df} = \alpha^* (0) + w^* \left(\frac{-d}{w^*c}\right) = \frac{-d}{c} < 0 \tag{A13}$$

which follows from (A11) and (A12).

$$\frac{dy^*}{df}=\frac{d\,[y\,(k^*,w^*)]}{df}=y_k\left(\frac{dk^*}{df}\right)+y_w\left(\frac{dw^*}{df}\right)=y_k\,(0)+y_w\,(0)=0 \tag{A14}$$

from (A10) and (A11).

$$\frac{dk^*}{de}=\frac{\begin{vmatrix} 0 & H_{wk} & 0 \\ \alpha g & \text{——} & (-\alpha wc) \\ wg & \text{——} & (-w^2c) \end{vmatrix}}{|H..|}=0, \tag{A15}$$

due to linear dependence between the first and third columns of the numerator.

$$\frac{dw^*}{de}=\frac{\begin{vmatrix} H_{kk} & 0 & 0 \\ \text{——} & \alpha g & (-\alpha wc) \\ \text{——} & wg & (-w^2c) \end{vmatrix}}{|H..|}=0, \tag{A16}$$

duetolinear dependencebetween thelast twocolumnsin thenumerator.

$$\frac{d\alpha^*}{de}=\frac{\begin{vmatrix} H_{kk} & H_{wk} & 0 \\ H_{wk} & H_{ww} & \alpha g \\ 0 & -\alpha wc & wg \end{vmatrix}}{|H..|}=\frac{-\frac{g}{wc}\,|H..|}{|H..|}=\frac{-g}{wc}<0, \tag{A17}$$

since the last column of the numerator equals $\frac{-g}{wc}$ times the last column of denominator, the first two columns of [H..] and the numerator are identical, and $g > 0$ by (A6).

$$\frac{d\,(\alpha w^*)}{de}=\alpha^*\frac{dw^*}{de}+w^*\frac{d\alpha^*}{de}=\alpha^*\,(0)+w^*\left(\frac{-g}{w^*c}\right)=\frac{-g}{c}<0. \tag{A18}$$

$$\frac{dy^*}{de}=y_k\left(\frac{dk^*}{de}\right)+y_w\left(\frac{dw^*}{de}\right)=y_k\,(0)+y_w\,(0)=0. \tag{A19}$$

$$\frac{dk^*}{d\omega} = \frac{\begin{vmatrix} 0 & H_{wk} & 0 \\ (1-\alpha) & \text{—} & (-\alpha wc) \\ (-w) & \text{—} & (-w^2c) \end{vmatrix}}{|H..|} = -\frac{w^2cH_{wk}}{|H..|} \gtrless 0. \quad \text{(A20)}$$

$$\frac{dw^*}{d\omega} = \frac{\begin{vmatrix} H_{kk} & 0 & 0 \\ \text{—} & (1-\alpha) & (-\alpha wc) \\ \text{—} & (-w) & (-w^2c) \end{vmatrix}}{|H..|} = -\frac{w^2cH_{kk}}{|H..|} < 0, \quad \text{(A21)}$$

since both $|H..|$ and $H_{kk}$ are $< 0$ by second order sufficient conditions.

$$\frac{d\alpha^*}{d\omega} = \frac{\begin{vmatrix} H_{kk} & H_{wk} & 0 \\ H_{wk} & H_{ww} & (1-\alpha) \\ 0 & (-\alpha wc) & (-w) \end{vmatrix}}{|H..|} = \frac{-w\,(H_{kk}H_{ww} - H_{wk}^2 + \alpha wc\,(1-\alpha)\,H_{kk}}{|H..|} \quad \text{(A22)}$$

$$= \frac{-w^2c\,(H_{kk}H_{ww} - H_{wk}^2) + \alpha w^2c^2H_{kk} - \alpha^2w^2c^2H_{kk}}{wc|H..|} = \frac{|H..| + \alpha w^2c^2H_{kk}}{wc|H..|}$$

by (A7), so

$$\frac{d\alpha^*}{d\omega} = \frac{1}{wc} + \frac{\alpha wcH_{kk}}{|H..|} > 0, \quad \text{(A23)}$$

since both $H_{kk}$ and $|H...| < 0$ by second order conditions.

$$\frac{d\,(\alpha^{*)}}{d\omega} \equiv \frac{d\,(\alpha^*w^*)}{d\omega} = \alpha^*\frac{dw^*}{d\omega} + w^*\frac{d\alpha^*}{d\omega}$$

$$= \frac{-\alpha^*w^{*2}cH_{kk}}{|H..|} + w^*\left(\frac{1}{w^*c}\right) + \frac{\alpha^*w^{*2}cH_{kk}}{|H..|} = \frac{1}{c} > 0. \quad \text{(A24)}$$

$$\frac{dy^*}{d\omega} = y_k\left(\frac{dk^*}{d\omega}\right) + y_w\left(\frac{dw^*}{d\omega}\right) = y_k\frac{w^{*2}cH_{wk}}{|H..|} + \frac{-w^{*2}cH_{kk}}{|H..|} \quad \text{(A25)}$$

$$= \frac{w^2c}{|H..|} (y_k H_{wk} - y_w H_{kk})$$

Substitution from (A0) yields

$$\frac{dy^*}{d\omega} = \frac{aw^2c}{|H..|} (y_k y_{wk} - y_w y_{kk}) . \tag{A26}$$

First order condition (4) may be rewritten $H_k = 0 = ay_k - r$, so

$$y_k = \frac{r}{a} . \tag{A27}$$

If first order condition (5) is expanded, and condition (6) is then substituted into this, and finally (A2) is employed, it is seen that

$$y_w = \frac{\omega}{a} \tag{A28}$$

Substitution of (A27) and (A28) into (A26) then yields

$$\frac{dy^*}{d\omega} = \frac{w^2c}{|H..|} (ry_{wk} - wy_{kk}) \gtrless 0 , \tag{A29}$$

with

$$< 0 \text{ if } y_{wk} > \frac{\omega}{r} y_{kk} ,$$

and

$$> 0 \text{ if } y_{wk} < \frac{\omega}{r} y_{kk} .$$

Now ordinarily $y_{wk} > 0$ for all but the most closely related inputs, like left handed labour and right handed labour. Following DEWEY [1975, p.193] our assumption will be that waste (w) and the conventional input (k) fall into the ordinary case, so that

$$y_{wk} > 0 \tag{A30}$$

by assumption. Thus, if $y_{kk}$ is relatively small, that is if y(k,w) exhibits relatively weakly increasing, constant or else decreasing marginal product of the conventional input one obtains

$$\frac{dy^*}{d\omega} < 0 \,. \tag{A31}$$

We shall consider (A31) to be the normal case, assume that it holds, however it should be borne in mind that

$$\frac{dy^*}{d\omega} > 0 \tag{A32}$$

remains possible for production functions $y(\cdot)$ exhibiting relatively strongly increasing marginal products of the conventional input k.

## REFERENCES

ARROW, K.J., 'Agency and the Market', Chapter 23 in: K.J. ARROW and M. INTRILIGATOR. *Handbook of Mathematical Economics* (North Holland: Amsterdam 1986).

BARON, D. and MYERSON, R. 'Regulating a Monopolist with Unknown Costs', *Econometrica*, 50(4), 1982.

BECKER, G.A. 'Crime and Punishment: An Economic Approach', *Journal of Political Economy*, 76, 169-217, 1968.

DEWEY, D., *Microeconomics: The Analysis of Prices and Markets* (Oxford: Oxford University Press, 1975).

EHRLICH, I., 'The Deterrent Effect of Capital Punishment: A Question of Life and Death', *American Economic Review* 65(3), 397-417, 1975.

GOTTINGER, H.W., *Economic Models of Solid Waste Management and Applications*, (Gordon & Breach Science Publishers; New York, 1991).

KWEREL, E., 'To Tell the Truth: Imperfect Information and Optimal Pollution Control', *Review of Economic Studies*, 44(3), 595-601 1977.

POLINSKY, A.M. and SHAVELL, S. 'The Optimal Use of Fines and Imprisonment', *Journal of Public Economics*, 24, 89-99, 1984.

REES, R., 'The Theory of Principal and Agent - Part 1' in: J.D. HEY and P.J. LAMBERT (eds), *Survey in the Economics of Uncertainty* (Basil Blackwell: Oxford 1987, 46-69).

SCHELLING, T., 'Economics and Criminal Enterprise' Chapter 7 in T. SCHELLING, *Choice and Consequence*, Harvard University Press: Cambridge, Mass. 1984.

STIGLER, G.J., 'The Optimum Enforcement of Laws', *Journal of Political Economy*, 78, pp. 526-536, 1970.

VARIAN, H.R. *Microeconomic Analysis*, (New York: W.W. Norton and Company, Inc., 1978).

WEITZMAN, M.L., 'Prices vs. Quantities', *Review of Economic Studies*, 41(4), pp.477-491, 1974.

ABSTRACT

Hazardous waste regulations require disposal in approved dumpsites, where environmental consequences are minimal but entry may be privately very costly. Imperfect policing of regulations makes the socially more costly option illicit disposal preferable form the perspective of the private decision maker. The existence of the waste disposal decision, its economic nature, production independence, and the control over environmental damage are key issues in the economics of hazardous waste management. This paper models a profit maximising, hazardous waste generating, monopolistic firm, a welfare maximizing regulatory agency, and investigates their behaviourial interactions.

ZUSAMMENFASSUNG

Regulierungen im Bereich gefährlicher Abfälle schreiben eine geeignete Deponierung in dafür vorgesehenen Sondermülldeponien vor. Zwar sind so (nach dem Stand der Technik) die Umweltrisiken minimal doch der Zugang der Unternehmen durch hohe Kosten belastet. Eine unzureichende Überwachung der Regulierungen macht die für die Gesellschaft kostenreiche illegale Entsorgung aus der Sicht privater Betriebe attraktiv. Das vorliegende Papier untersucht die strategische Situation eines gewinnmaximierenden, Sondermüll erzeugenden monopolistischen Unternehmens und einer wohlfahrtsoptimierenden regulatorischen Behörde.

RESUME

Des régulations dans le domaine des déchets dangereux imposent une déposition spécifique dans les lieux prévus pour ces déchets. De cette façon les risques écologiques sont bien minimisés (correspondant à l'état technologique) mais l'accès aux déponies cause des dépenses considérables aux entreprises. Une inspection insuffisante attire les entreprises à se défaire des déchets de manière illégale, à des coûts sociaux sensibles. Cet article explore la situation stratégique d'une entreprise monopolistique produisant des déchets dangereux.